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Renewable Acrylic Acid

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Abstract
Acrylic acid is an important industrial chemical, used as a raw material in a wide variety of consumer end products. The present predominant source of acrylic acid is from the partial oxygenation of propene, produced as a by-product in the industrial production of ethylene and gasoline. Both processes depend heavily on the processing of petrochemicals as the base raw material. The purpose of this process is to produce acrylic acid from renewable carbon sources (such as corn or sugarcane) in an economically preferential manner. Our process has used genetically recombinant *Escherichia coli (E. coli)* to ferment the carbohydrate content of the proposed feedstock to 3-hydroxypropionic acid (3-HP) which is then dehydrated in the presence of strong acid catalyst (phosphoric acid) to form acrylic acid. The acrylic acid is then purified to the standard required for use as a polymer raw material (99.98% by mass) with total capacity of 160,000 MT/year of product.

This design analyzes two proposed locations, the US Midwest or Brazil, and their associated renewable feedstocks, corn or sugarcane juice, respectively. This report investigates the relative economic attractiveness of each option. The US case requires location near an existing industrial ethanol fermentation plant to give easy access to dry-ground corn as a carbohydrate source. This case yields an IRR of 17.56% and an overall NPV of $35.2 million at a 15% discount rate. The Brazil case has comparatively cheaper feedstock, however because of seasonality and total usable carbohydrate content, it requires a greater mass of feedstock and increased capital investment relative to the US case. The NPV difference of the two cases is extremely sensitive to the assumed price of sugarcane juice which has recently shown extraordinary volatility. Based on this analysis, the US location seems most promising; however, detailed laboratory level studies are needed to confirm the profitability and assumptions made.

Renewable Acrylic Acid

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School of Engineering and Applied Science

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April 10, 2012

Advisor: Dr. Robert Riggleman

Primary Consultant: Stephen M. Tieri

Dupont Engineering Research & Technology

Professor Leonard Fabiano
Dr. Robert Riggleman
Department of Chemical and Biomolecular Engineering
University of Pennsylvania
Philadelphia, PA 19104

April 10, 2012

Dear Professor Fabiano and Dr. Riggleman,

Enclosed you will find the process design for the renewable production of acrylic acid. The proposed design utilizes genetically recombinant *Escherichia coli* to ferment sugar from renewable corn feedstock to 3-hydroxypropionic acid, which is then dehydrated selectively in the presence of phosphoric acid catalyst to produce the desired acrylic acid product. The acrylic acid product is then purified to specification for use as a polymer raw material. The proposed plant is designed to operate in the US Midwest, in partnership with a corn dry-grind ethanol production plant which will provide enzyme digested corn feedstock at local market price, and will produce the specified 160,000 MT/year of polymer grade acrylic acid.

The proposed design process is expected to deliver an IRR of 17.56% with a total NPV of $35.2 million at a 15% discount rate. Simulations of the process have been carried out using SuperPro Designer and Aspen Plus v7.3. Economic analysis was carried out using Aspen IPE and the methods and spreadsheets contained in *Process Design Principles*, 3rd Edition by *Seider, Seader, Lewin, and Widagdo*.

Please feel free to contact us should any questions regarding the methodology of completion or process specifics arise.

Sincerely,

Andrew Cie	Stephen Lantz	Roy Schlarp	Metaxia Tzakas

Table of Contents

Tables

<u>Figures</u>

Abstract

Acrylic acid is an important industrial chemical, used as a raw material in a wide variety of consumer end products. The present predominant source of acrylic acid is from the partial oxygenation of propene, produced as a by-product in the industrial production of ethylene and gasoline. Both processes depend heavily on the processing of petrochemicals as the base raw material. The purpose of this process is to produce acrylic acid from renewable carbon sources (such as corn or sugarcane) in an economically preferential manner. Our process has used genetically recombinant *Escherichia coli (E. coli)* to ferment the carbohydrate content of the proposed feedstock to 3-hydroxypropionic acid (3-HP) which is then dehydrated in the presence of strong acid catalyst (phosphoric acid) to form acrylic acid. The acrylic acid is then purified to the standard required for use as a polymer raw material (99.98% by mass) with total capacity of 160,000 MT/year of product.

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Introduction and Background Information

Acrylic acid is a versatile monomer used to form important polymers used in the manufacturing of products such as plastics, coatings, adhesives, elastomers, floor polishers and paints. It is most commonly used as a feedstock for commodity acrylic esters which account for approximately 65 to 70% of the products produced from acrylic acid. Polyacrylic acids are able to provide a number of desirable qualities for polymeric materials including: color stability, clarity, heat and aging resistance, good weatherability, low temperature flexibility, and resistance to acid and bases. As such, they are used to form super absorbent polymers, polyacrylates, and detergent builders which are used in disposable baby diapers, feminine hygiene products, water treatment and detergents. The other major use of acrylic acid is in the form of glacial acrylic acid, which makes up the remainder 30% of products formed from acrylic acid. This can be used in the production of polyacrylic acids or copolymers found in emulsions, plastics, acrylic rubbers and textile treatment. These are then used in the production of coatings, adhesives, sealants, automotives, and textiles.

Acrylic acid is typically obtained from the catalytic partial oxidation of propene which is a byproduct of ethylene and gasoline production as shown in the following equation:

$$H_2C = CHCH_3 + \frac{3}{2}O_2 \longrightarrow H_2C = CHCOOH + H_2O \quad (\Delta H_R = -254.1\frac{kJ}{mol})$$

Due to the high demand for acrylic acid coupled with volatile crude oil prices, alternative methods have been studied and tested as potential replacements for the process in order to reduce the dependence of acrylic acid demand on gasoline. The need for cheaper alternatives has grown, encouraging companies to look into renewable alternatives to produce acrylic acid in a more eco-friendly and economically comparable manner.

With this effort, R&D programs have developed a genetically engineered strain of *E. coli* cells. These cells have an altered metabolic pathway where the pyruvate products of glycolysis, the process that normally turns glucose into energy rich ATP, is modified to produce 3-hydroxypropionic acid. This is done by using lactic acid and acrylyl-CoA as intermediaries. The precise microbiology of this metabolic pathway is outside the scope of this project and is described in US Patent 7,186,541. This microorganism has been tested successfully in small scale pilot trials and shows the potential to produce 3-HP in large quantities. Due to this success, it is believed that the *E. coli* production is ready to be scaled up to commercial size production.

This report investigates using corn from the US Midwest and sugarcane from Brazil as the sources of glucose for 3-HP production. The bio-acrylic acid manufacturing facility would be built attached to an existing sugar processing facility in the chosen location. This will ensure a consistent raw material supply to the designed process.

Following the formation of 3-HP, the chemical is dehydrated to form the desired acrylic acid product. The dehydration reaction is slightly exothermic (ΔH_R = .35 kJ/mol) and is done in the presence of a phosphoric acid catalyst. Using first a continuously stirred tank reactor (CSTR) and then a reactive distillation tower, it is possible to achieve a conversion of 3-HP to acrylic acid of over 99%. Following this reaction, due to large differences in volatility between water, 3-HP, acrylic acid, and phosphoric acid as well as the absence of azeotropes in the system, it is possible to design a product stream consisting of over 99.99% acrylic acid. The overall goal of this process is to produce 160,000 MT/year of acrylic acid.

A further benefit of this process design is the low level of impact it has on the environment. The glucose sources of either corn or sugarcane are fully renewable and the process only uses a small amount of carbon dioxide to eliminate the chance of decarboxylation side reactions resulting in a carbon neutral process. Compared with the current industry norm that consumes non-renewable fossil fuels and produces a large bi-product of carbon dioxide, this is a significant improvement.

Project Charter

Project Name **Renewable Acrylic Acid**

Project Champion Stephen Tieri (DuPont), Dr. Rob Riggleman

Project Leader Ryan A. Cie, Stephen J. Lantz, Roy P. Schlarp, Metaxia M. Tzakas

Specific Goals Design and determine the economic viability of a plant that produces competitive amounts of acrylic acid via the fermentation of renewable sources using a microorganism that ferments the sugar-source to 3-hydroxypropionic acid that is then dehydrated to form acrylic acid.

Project Scope In Scope:

- Full process design of a plant that produces 160,000 MT/yr acrylic acid
- Use corn or sugarcane, renewable resources, as the feedstock for this process
- Determine economic viability of the proposed plant and the profitability of the venture should it be determined to be economically viable.
- Provide a short description of the sizing needed for corn or sugarcane processing plants

Out of scope:

- Specific biochemistry of the proposed microorganism that will ferment the sugar source to 3-hydroxypropionic acid

- Determine the costing and specific machinery settings of the processing plants for sugarcane and corn.

Deliverables

- Full Plant Design
- Economic Analysis of the process
- Approximate sizing for feedstock suppliers

Timeline Deliverables completed by April 10, 2012

Innovation Map

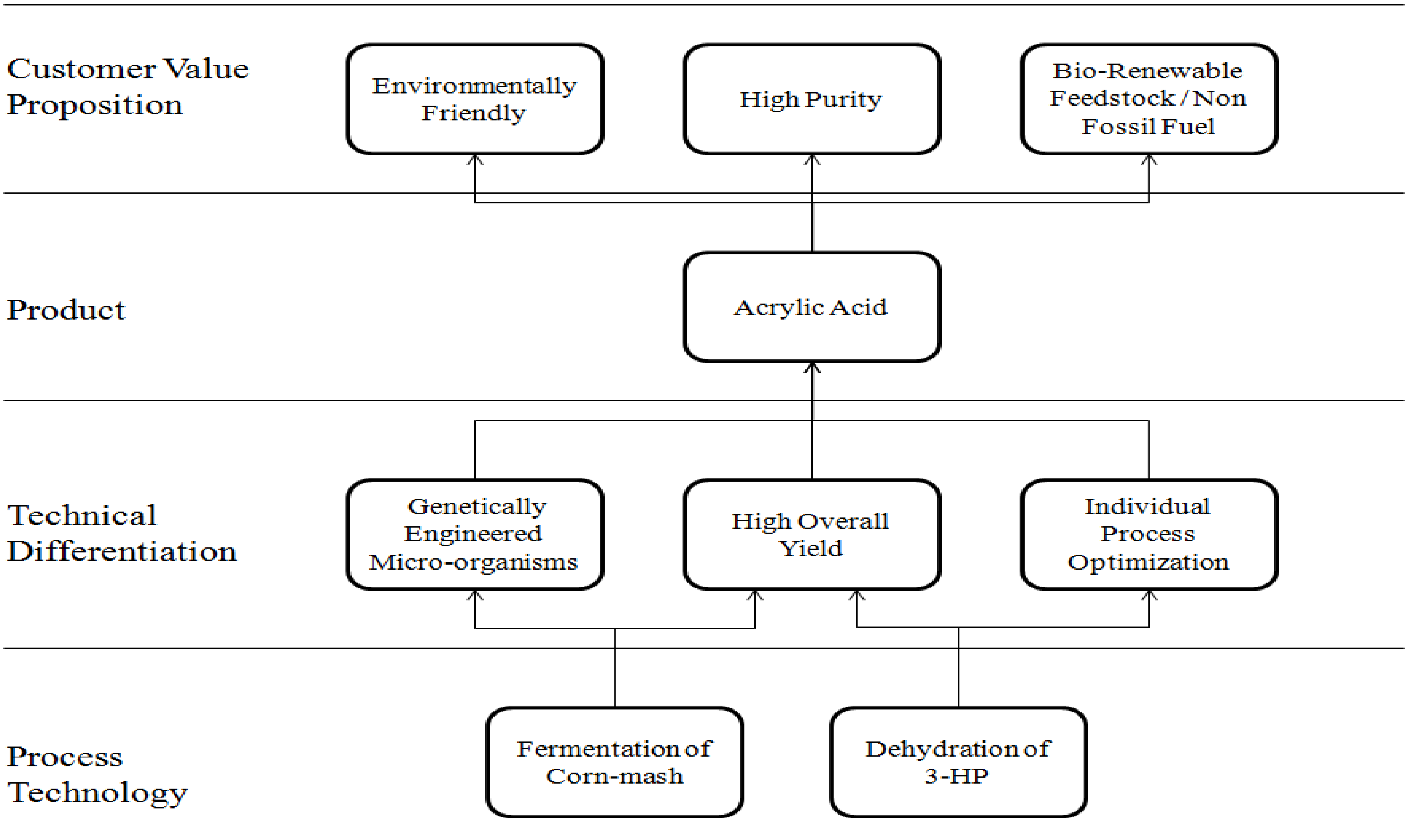

Figure 1. Innovation Map

Discussion

The problem statement for the proposed process lays out that the final product of the process should be polymer grade acrylic acid, which has a standard specification of purity (99.99% purity by mass). Additionally, the problem statement describes how the process should be environmentally friendly, and is partially motivated by environmental concerns for the impact of existing processes for acrylic acid production. A significant part of this low environmental impact specification is that the feedstocks used should be renewable, and not contain fossil fuel feedstock. Thus, the required specifications for the proposed process are shown as part of the customer value proposition for the process.

The technological differentiation for the process results primarily from the new genetically modified micro-organisms (*E. coli*) used in the fermentation. These micro-organisms are used to ferment the available carbohydrate (glucose) and are a significant technological differentiation from the existing processes for acrylic acid production. Flowing from this main differentiation is a high overall yield for the separation and reaction process and individual process optimization available because of the fundamentally new processes used. Whereas existing acrylic acid production uses petrochemical processing, using water and a 3-HP intermediate allows easier separation and reaction, and allows different regions of the overall process to be optimized independent of each other, unlike those used in petrochemical processing (where acrylic acid production is primarily a byproduct and completely a result of existing processes, optimized for primary product production).

Process technology used in the proposed design has long been known and is heavily studied. It can be functionally broken down in the fermentation process (and production of the intermediate 3-HP), and the high yield reaction and separation of 3-HP to acrylic acid, which uses well characterized process units such as distillation column, reactors, heat exchangers and pump. The process technology therefore is not of significant importance for the overall innovation of the proposed design and builds on already well known and characterized processes.

Concept Stage

Market and Competitive Analysis

Due to its use in a number of applications including adhesives, paints, diapers, and detergents, there is an $8 billion dollar market for acrylic acid, with a predicted growth rate of approximately 3 to 5 percent per year.[1]

Acrylic acid has a wide variety of uses. First, because of its structure, it can act as a vinyl compound or as a carboxylic acid in reactions. Second, it can also act as copolymers with esters, chlorides, vinyl acetate, butadiene and ethylene which, along with homopolymers of acrylic acid, can form acidic water-soluble compounds or alkali/ammonium salts. These particular products can then be used in thickening agents, dispersing agents, protective colloids and wetting agents. Superabsorbent polymers (SAP), which are lightly cross linked polyacrylic acid salts, are used for fluid retention for products such as diapers and agriculture. Depending on the amount of acrylic acid present in copolymers, polymers with different properties can be formed, each of which can be used for a variety of purposes. Semi-soluble and insoluble polymers can be produced by copolymers with less than 50% acrylic acid which are used as intermediates and binders for printing inks and coatings. Meanwhile, oil and solvent-resistant polymers can be formed by copolymers with very small amounts of acrylic acid.

Furthermore, market growth in China has encouraged adoption of production strategies from companies in the United States. This includes using polymers and copolymers to produce different types of materials that are needed. Due to this incorporation of U.S. techniques and applications, China, along with an equally fast market growth trend in India, has drastically added to the growing demand for acrylic acid.[2]

[1] [46] SustainableBusiness.com
[2] [18] Falholt

In terms of competition, producing an acrylic acid plant would face a number of competitive challenges that would have to be overcome. First, there is competition against traditional acrylic acid production methods, namely through the use of petrochemicals. These producers have the advantage of having existing scale and maximized energy efficiency, fixed cost reduction, improved maintenance and plant reliability. It also has the added benefits of having existing sourcing/supply chains, value engineering, and reduced on-stream time. Another source of competition comes from direct competitors, specifically, companies targeting the same market (such as BASF and the DOW/OPX Biotech partnership) who are developing the same general process to accommodate the same market. According to reports, DOW and OPX Biotech plan to bring about commercially available acrylic acid to the market in 3 to 5 years which would probably reduce profitability through application of downward price pressure. [3] Since renewable chemicals face the challenges of having to compete on price and performance and no subsidies or infrastructure, there are a lot of challenges that the renewable chemicals industry must overcome in order to be competitive (in terms of cost-effectiveness and optimization levels). Nevertheless, the profitability of the proposed process justifies further exploration of the market. A summary of the market and competitive environment is shown in Table 1 in the form of a Porter's Five Forces analysis. Additionally a summary SWOT analysis is shown in Table 2. As can be seen in these tables, the market position of the proposed plant is relatively favorable and presents reasonably attractive opportunities and allows leverage of significant economic strengths.

[3] [46] SustainableBusiness.com

Porter's Five Forces Analysis		
Category	Relative Power	Notes
Suppliers	Low	Corn is a commodity feedstock, commonly used in industrial process. Additionally, there are numerous suppliers all in direct competition
Customers	Low	Well established and commoditized market. Many independent chemical processors as customers.
Threat of New Entrants	High - Medium	There are numerous well capitalized chemical companies who have expressed interest in the manufacturing methods. These new entrants could put downward pressure on product price and affect process profitability
Threat of Subsitute Products	Medium	Though there is no direct substitute for acrylic acid, rising input prices could make alternative copolymers economically preferential. Additionally the high rate of technological innovation presents reasonable risks of alternative compounds being introduced to the market.
Competitive Rivalry	High	Acrylic acid production is a highly capitalized and well established process presenting significant competitive pressure to the process. Additionally, existing technology is well established and represents an initial cost advantage during development

Table 1. Porter's Five Forces Summary

SWOT Analysis	
Category	Notes
Strengths	Well established market, technological advantages, margins and cost advantages
Weaknesses	Strong competition, unproven technology, start up cost requirements
Opportunities	Renewable feedstock, no exposure to petrochemical shortages
Threats	Flucuating raw material prices, especially media and energy requirements

Table 2. SWOT Analysis Summary

Customer Requirements

Customer requirements for this process are relatively standardized based on the existing market for high purity, polymer grade acrylic acid. According to the problem statement, the purity of the acrylic acid produced is required to be at the specified industry standard, which is 99.99% by mass purity. This is accomplished by the proposed process and allows for contingencies in unanticipated impurities in any feedstock or raw material used.

Delivery of acrylic acid is in the form of a purified liquid, so the product is produced at specification and immediately stored and pumped for delivery when requested. Storage and shipment temperatures should be kept in the range of 59-77^{o}F to prevent any undesired reactions. Acrylic acid should also be stored under atmospheric pressure air and not other inert gasses. Because acrylic acid polymerizes easily in the presence of heat, light, or metals, typically a polymerization inhibitor (such as hydroquinone at a concentration 200ppm) is added prior to shipment. Due to its corrosive nature, it must be shipped in either stainless steel, aluminum, or polyethylene drums. It must be labeled as corrosive, flammable, and dangerous to the environment.

Preliminary Process Synthesis

Acrylic acid is typically produced through the catalytic partial oxidation of propene as given by the following overall equation:

$$C_3H_6 + \frac{3}{2}O_2 \longrightarrow C_3H_4O_2 + H_2O \tag{1}$$

This reaction is actually a two-step process where propene is first oxidized to the intermediate species, acrolein (C_3H_4O), before being partially oxidized to acrylic acid. This is shown in the following reaction steps:

$$C_3H_6 + O_2 \longrightarrow C_3H_4O + H_2O \tag{2a}$$

$$C_3H_4O + \frac{1}{2}O_2 \longrightarrow C_3H_4O_2 \tag{2b}$$

However, besides being highly dependent on propene which is a byproduct of oil refining and natural gas processing, this process experiences various side reactions as listed below:

$$C_3H_4O + \frac{7}{2}O_2 \longrightarrow 3\,CO_2 + 2\,H_2O \tag{3a}$$

$$C_3H_4O + \frac{3}{2}O_2 \longrightarrow 3\,C_2H_4O_2 + 2\,CO_2 \tag{3b}$$

$$C_3H_6 + \frac{9}{2}O_2 \longrightarrow 3\,CO_2 + 3\,H_2O \tag{3c}$$

In order to reduce dependence on fossil fuels and to avoid side reactions, an alternative method of forming acrylic acid is through the dehydration of 3-hydroxypropionic acid (3-HP). Beginning with a source of glucose ($C_6H_{12}O_6$), a special strain of *E. coli* produces 3-HP via a biosynthetic pathway. This method and process is outlined in detail in U.S. Patent 2011/0124063

A1 and U.S. Patent 2011/0125118 A1. The overall reaction of glucose to 3-HP under ideal conditions is shown below.

$$C_6H_{12}O_6 \longrightarrow 2C_3H_6O_3 \tag{4a}$$

The 3-HP can then be dehydrated with a phosphoric acid catalyst to form acrylic acid. The method for this procedure is provided in U.S. Patent 2011/0105791 A1. Below is the overall dehydration reaction of 3-HP to acrylic acid.

$$C_3H_6O_3 \longrightarrow C_3H_4O_2 + H_2O \text{ in the presence of phosphoric acid catalyst} \tag{4b}$$

The yield of 3-HP is dependent on the presence of oxygen in the fermentation vessel. The *E. coli* fermentation can occur in either aerobic or anaerobic conditions, but with significant differences in overall yield which were considered in determining the most cost effective way to produce the necessary amount of 3-HP. Aerobic conditions had a yield 3.7 times greater than that of anaerobic conditions (1.85 moles of 3-HP per mole of glucose compared to 0.5 moles of 3-HP per mole of glucose). If anaerobic conditions were to be used, this would result in fermenters that would need to be 3 times as large as ones designed for aerobic fermenters. This size difference would cost approximately $925,000. In addition, the fermenter product stream for anaerobic conditions would only contain 2.48% 3-HP which would require significantly more downstream processing resulting in increased equipment and utility costs. Hence, this fermentation section was designed to implement aerobic conditions. Additionally, it was determined that airlift fermenters would be the most economically effective fermentation vessels for the process. A schematic figure of an airlift fermenter, which shows how air enters the bottom of the fermenter and creates a current to agitate the mixture, is shown in Figure 2. Airlift Fermenter Schematic.

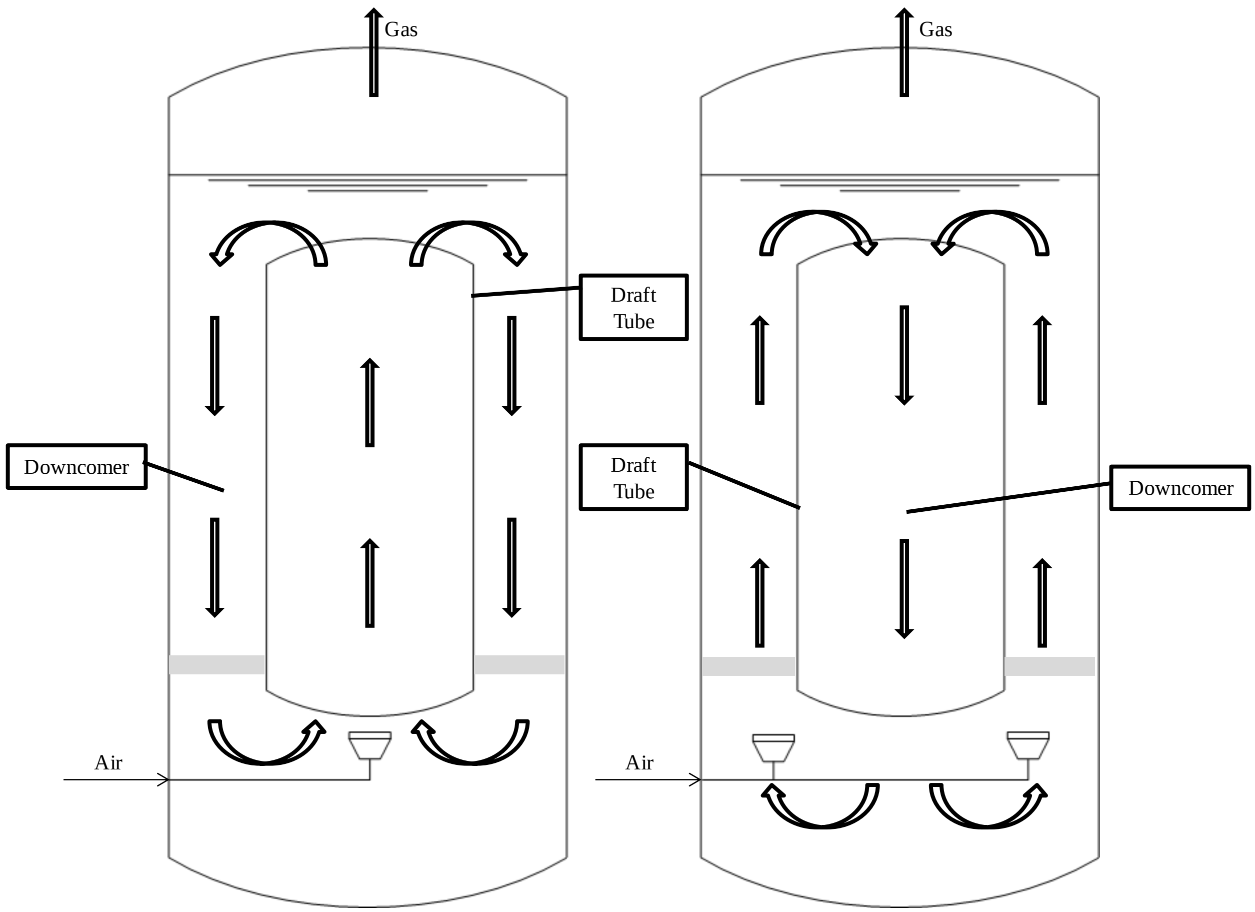

Figure 2. Airlift Fermenter Schematic

Assembly of Database

Input Costs

The input cost for water, priced at $\$2.00 \times 10^{-4}$ per kg, was taken from *Seider, Seader, Lewin, and Widagdo*. Input costs for carbon dioxide, phosphoric acid, and the nutrient media were derived using a method recommended by Bruce Vrana (DuPont). A multiplying factor of .0571 was used to reduce purchase prices from Fischer Scientific because of the large commercial quantities purchased for this process. This factor was derived by taking the ratio of Fischer Scientific prices compared to known bulk prices paid by DuPont. [4] This resulted in the nutrient media costing $4.57 per kg and phosphoric acid costing $5.51 per kg. The price of corn used was $.28 per kg as according to Chicago Mercantile Exchange. Carbon dioxide, provided industrially in 10,000 kg pressurized tanks, is available for $1.52/kg.[5]

Thermodynamic Properties

Thermodynamic properties for water, phosphoric acid, and carbon dioxide were estimated using Aspen. Properties for 3-HP were provided by David Kolesar of Dow Chemicals. .

Scheduling

Scheduling for the batch portion of the described process was completed using SuperPro Designer. *E. coli* fermentation time was taken to be 24 hours as described in US Patent 6,852,517. Joye Bramble (Morphotek) and Bruce Vrana (DuPont) were consulted on estimating the time for the Steam-In-Place and Clean-In-Place procedures in the fermenters.

[4] This pricing suggestion was supplied by Mr. Bruce Vrana.
[5] [52] Haas Group International Quote

Feasibility, Development, Manufacturing and Product Introduction

Process Flow Diagram and Material Balances

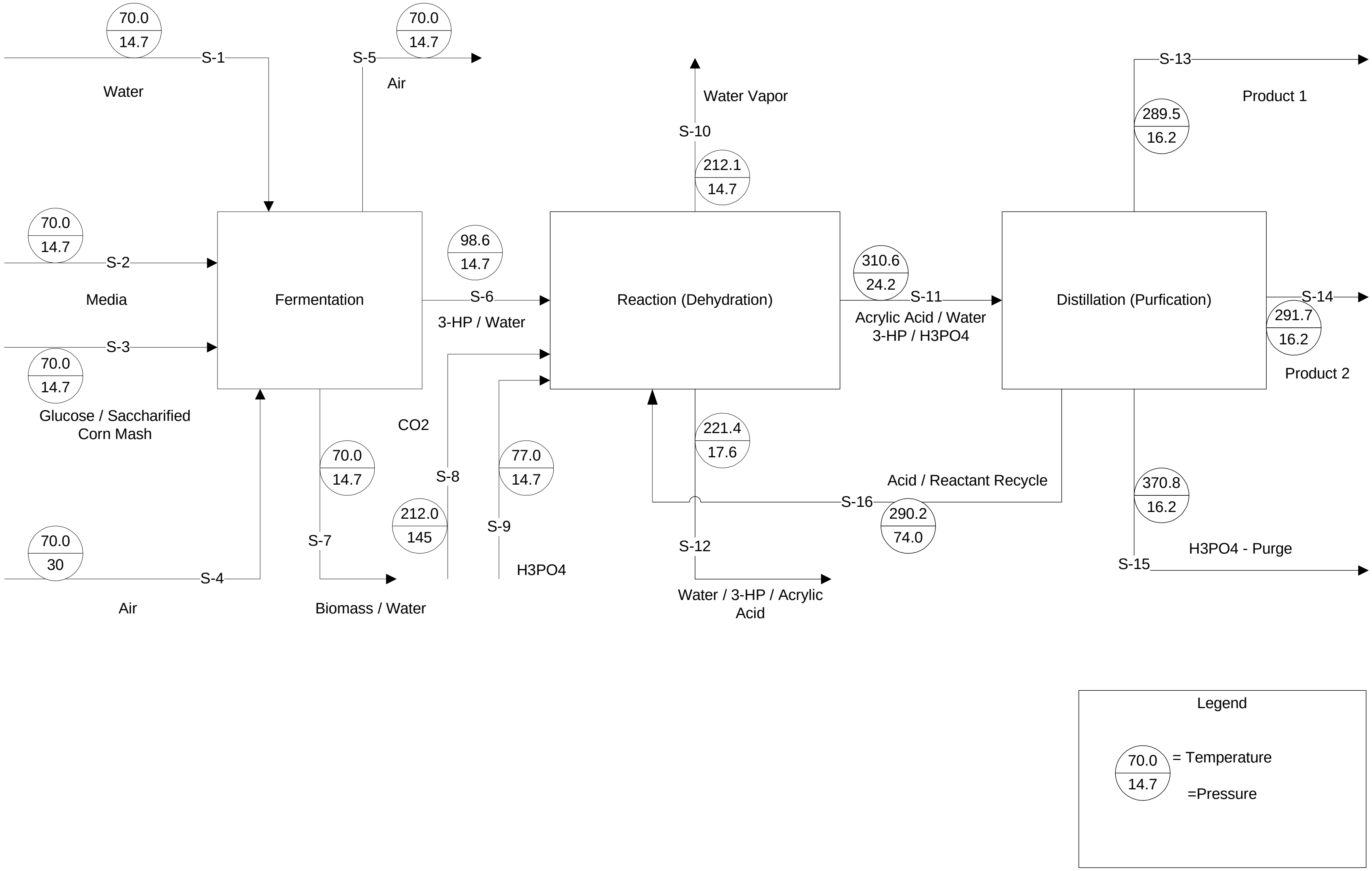

Figure 3. Overall Process Flowsheet

Stream Number	S-1	S-2	S-3	S-4	S-5	S-6	S-7	S-8
Temperature (°F)	70	70	70	70	70	98.6	70	212.0
Pressure (psi)	14.7	14.7	14.7	30	14.7	14.7	14.7	145.0
Vapor Fraction	0	0	0	1	1	0	0	1.0
Mass (lb/hr)	1,422,304	22,306	139,859	27,088	27,088	728,166	231,893	2.2
Mole (lb-mol/hr)	78,929	207	3,098	776,985	776,985	37,429	12,263	0.1
Flow Time per Batch	16	16	16	24	24	Continuous	12	Continuous
Volume (gpm)	2,860	45	181	45,112	45,112	1,458	464	0.3
State	Liquid	Liquid	Liquid	Vapor	Vapor	Liquid	Liquid	Vapor
Mass Components (lb/hr)								
3-HP	-	-	-	-	-	67,342	-	-
Acrylic Acid	-	-	-	-	-	-	-	-
Air	-	-	-	26,820	26,820	-	-	-
Biomass	-	-	-	-	-	-	42,253	-
CO2	-	-	-	-	-	-	-	2.2
Glucose	-	-	139,859	-	-	-	-	-
Phosphoric Acid	-	-	-	-	-	-	-	-
Media	-	22,306	-	-	-	-	-	-
Water	1,422,304	-	-	-	-	660,823	189,641	-

Stream Number	S-9	S-10	S-11	S-12	S-13	S-14	S-15	S-16
Temperature (°F)	77.0	212.1	310.6	221.4	289.5	291.7	370.8	290.2
Pressure (psi)	14.7	14.7	24.2	17.6	16.2	16.2	16.2	74.0
Vapor Fraction	-	0.2	-	1.0	-	-	-	-
Mass (lb/hr)	22.1	658,646.8	462,110.8	21,468.7	4,150.7	14,628.9	31.5	410,920.4
Mole (lb-mol/hr)	0.2	36,304.9	6,441.3	1,140.9	56.4	203.0	0.4	5,739.2
Flow Time per Batch	Continuous	Continuous	Continuous	Continuous	Continuous	Continuous	Continuous	Continuous
Volume (gpm)	0.1	384,109.3	1,041.0	59,040.4	8.4	97.2	0.1	909.5
State	Liquid	Mixed	Liquid	Vapor	Liquid	Liquid	Liquid	Liquid
Mass Components (lb/hr)								
3-HP	-	63.9	199.1	-	0.0	0.1	2.0	-
Acrylic Acid	-	-	458,815.0	1,217.2	4,141.8	14,628.8	7.5	410,037.4
Air	-	-	-		-	-	-	-
Biomass	-	-	-		-	-	-	-
CO2	-	-	-	2.2	0.0	-	-	-
Glucose	-	-	-		-	-	-	-
Phosphoric Acid	22.1	-	2,204.7		-	-	22.1	-
Media	-	-	-		-	-	-	-
Water	-	36,241.0	891.9	20,249.3	883.0	-	-	883.0

Table 3. Overall Process Stream Table

Overall Process Outline

The overall process has been divided into three main parts: fermentation, dehydration, and distillation. In order to successfully produce acrylic acid from biomass, first, glucose is converted to 3-HP via the aerobic fermentation of *E. coli*. The spent fermentation broth is sterilized and centrifuged to remove any biomass. The remaining 3-HP and water solution is heated and pressurized in multi-effective evaporation flash vessels to drive water off from solution. This concentrated 3-HP stream flows through a pressure vessel with phosphoric acid, which acts as a catalyst in the dehydration reaction, converting 3-HP to acrylic acid in a roughly 30% yield. This product flows through a reactive distillation tower, which is maintained with a carbon dioxide atmosphere to prevent decarboxylation side reactions. The resulting acrylic acid is further distilled and partially recycled to ensure near complete reaction of 3-HP, recovery of the acid catalyst, and purification of the acrylic acid to a specified purity.

As seen in the overall process diagram, nutrients, air, glucose, and water flow into the fermentation process. Biomass flows out of the centrifuge, which is shown as S-7 in the Process Flow Diagram. The 3-HP and water mixture (S-6) flows out and enters an overall dehydration process.

In the overall dehydration process, carbon dioxide and phosphoric acid flow into the process (S-8 and S-9). Waste water streams from the reactive distillation tower (S-12), and from the flash evaporation process (S-10) are removed and flow to waste water treatment plants. Further purification of the newly created acrylic acid is necessary so S-11 enters into distillation process units. Acid is purged from the process via stream S-15, acid catalyst is recycled back into the reaction units, and pure acrylic acid product is collected (S-13 and S-14). The proposed process produces 21,473.3 kg (47,327.2 lb) of acrylic acid per hour which meets the 160,000 MT / year specification in the problem statement. The separation trains within the process require significant amount of steam to drive reboilers, as well as cooling water to provide cooling utility for distillation column condensers. Utility requirements are not shown explicitly on the overall process flow diagram, but are summarized in Table 14 through Table 18, which contain process energy requirements and utility requirement summaries.

Section 1 - Mixing / Blending Section

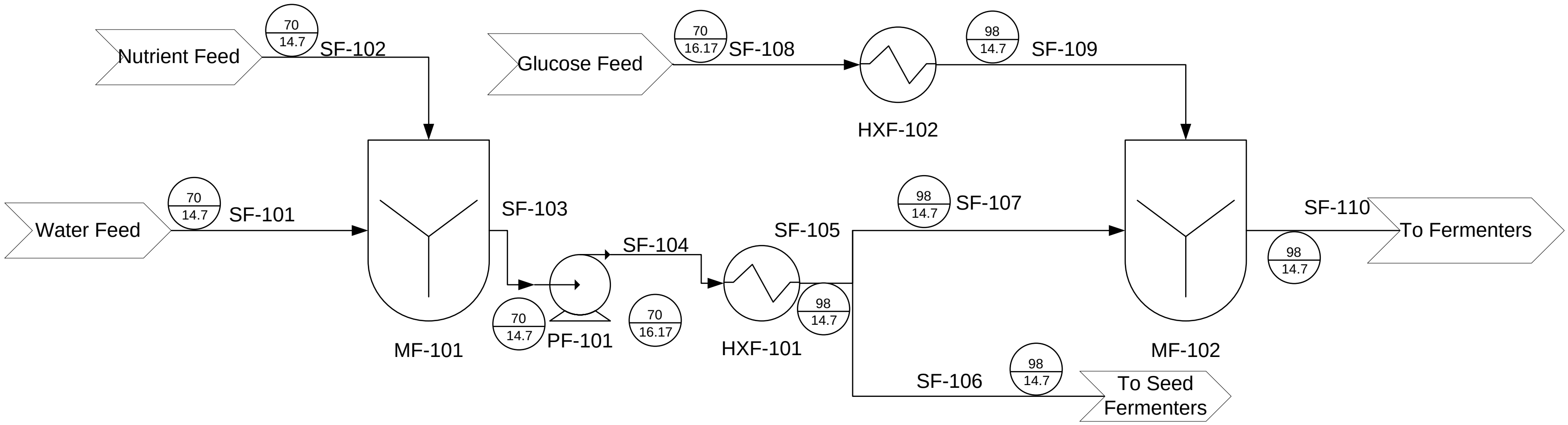

Figure 4. Mixing Section Flowsheet

Stream Number	SF-101	SF-102	SF-103	SF-104	SF-105	SF-106	SF-107	SF-108	SF-109	SF-110
Temperature (°F)	70.0	70.0	70.0	70.0	98.0	98.0	98.0	70.0	98.0	98.0
Pressure (psi)	14.7	14.7	14.7	16.2	14.7	14.7	14.7	14.7	14.7	14.7
Vapor Fraction	-	-	-	-	-	-	-	-	-	-
Mass (lb/hr)	1,422,304.1	22,306.2	VARIES	VARIES	VARIES	126,757.5	1,436,688.0	139,858.8	139,858.8	1,576,546.7
Mole (lb-mol/hr)	78,929.2	206.5	VARIES	VARIES	VARIES	6,917.2	78,703.4	3,097.6	3,097.6	79,477.8
Flow Time per Batch	16.0	16.0	-	-	-	TOTAL	16.0	16.0	16.0	16.0
Volume (gpm)	2,860.3	44.9	-	-	-	31.6	1,419.5	181.4	181.4	1,577.2
State	Liquid	Liquid	Liquid	Liquid	Liquid	Liquid	-	Liquid	Liquid	Liquid
Molar Components (lb-mol/hr)										
3-HP	-	-	-	-	-	-	-	-	-	-
Air	-	-	-	-	-	-	-	-	-	-
Biomass	-	-	-	-	-	-	-	-	-	-
Glucose	-	-	-	-	-	-	-	3,097.6	3,097.6	774.4
Media	-	206.5	-	-	-	23.4	205.0	-	-	205.0
Water	78,929.2	-	-	-	-	6,893.8	78,498.3	-	-	78,498.3
Mass Components (lb/hr)										
3-HP	-	-	-	-	-	-	-	-	-	-
Air	-	-	-	-	-	-	-	-	-	-
Biomass	-	-	-	-	-	-	-	-	-	-
Glucose	-	-	-	-	-	-	-	139,858.8	139,858.8	139,858.8
Media	-	22,306.2	-	-	-	2,532.0	22,148.0	-	-	22,148.0
Water	1,422,304.1	-	-	-	-	124,225.5	1,414,540.0	-	-	1,414,540.0

Table 4. Mixing Section Stream Table

Section 2 – Seed Fermentation

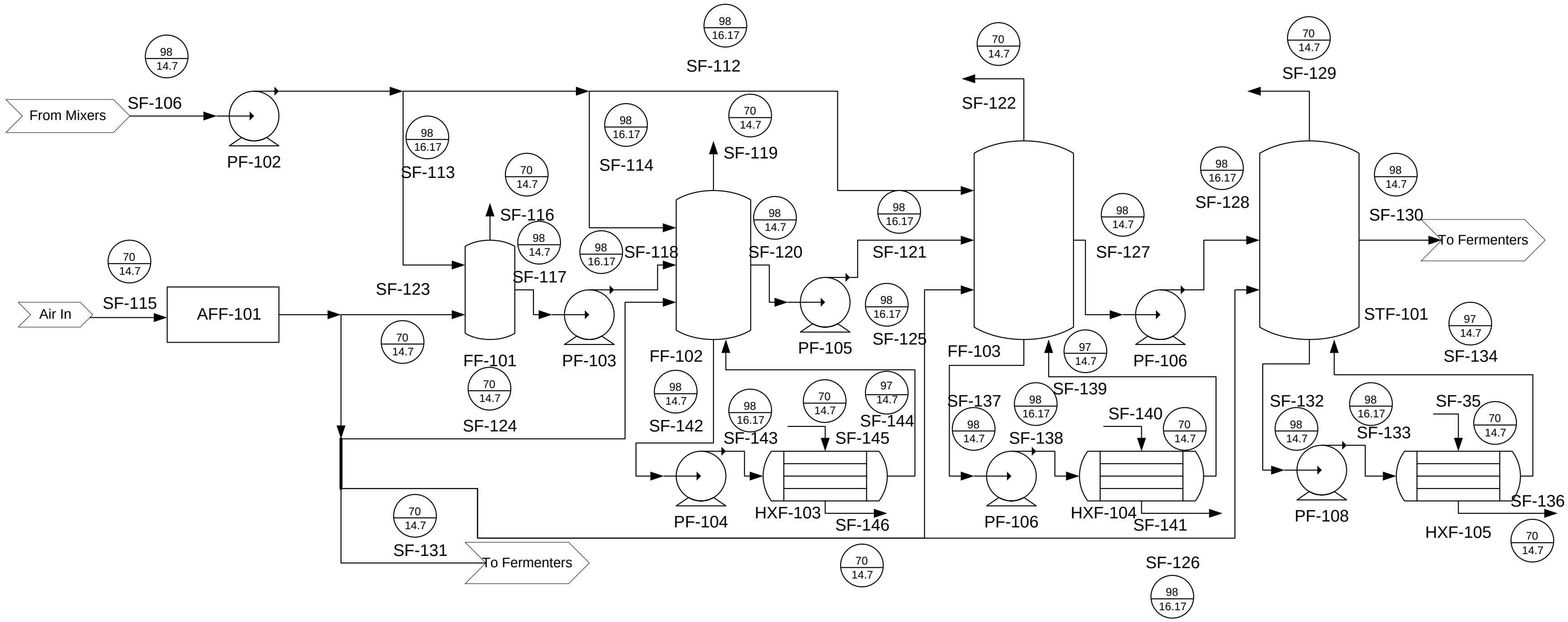

Figure 5. Seed Fermentation Section Flowsheet

Stream Number	SF-106	SF-112	SF-113	SF-114	SF-115	SF-116	SF-117	SF-118	SF-119	SF-120
Temperature (°F)	98.0	98.0	98.0	98.0	70.0	70.0	98.0	98.0	70.0	98.0
Pressure (psi)	14.7	16.2	16.2	16.2	30.0	14.7	14.7	16.2	14.7	14.7
Vapor Fraction	-	-	-	-	1.0	1.0	-	-	1.0	-
Mass (lb/hr)	126,757.5	168,165.0	12.6	2,522.5	27,088.2	0.0	12.7	12.7	0.7	845.1
Mole (lb-mol/hr)	6,917.2	9,176.6	0.7	138.2	776,984.7	0.0	0.7	0.7	0.0	46.7
Flow Time per batch (hr)	TOTAL	0.8	0.3	0.3	24.0	24.0	0.3	0.3	24.0	0.8
Volume (gpm)	31.6	42.1	0.0	0.2	45,111.6	0.0	0.0	0.0	1.1	0.2
State	Liquid	Liquid	Liquid	Liquid	Vapor	Vapor	Liquid	Liquid	Vapor	Liquid
Molar Components (lb-mol/hr)										
3-HP	-	-	-	-	-	-	-	-	-	-
Air	-	-	-	-	776,984.7	0.0	-	-	0.0	-
Biomass	-	-	-	-	-	-	0.0	0.0	-	0.7
Glucose	-	-	-	-	-	-	-	-	-	-
Media	23.4	31.1	0.0	0.4	-	-	-	-	-	-
Water	6,893.8	9,145.5	0.7	137.9	-	-	0.7	0.7	-	46.0
Mass Components (lb/hr)										
3-HP	-	-	-	-	-	-	-	-	-	-
Air	-	-	-	-	26,820.0	0.0034	-	-	0.7	-
Biomass	-	-	-	-	-	-	0.3	0.3	-	16.9
Glucose	-	-	-	-	-	-	-	-	-	-
Media	2,532.0	3,363.3	0.3	38.0	-	-	-	-	-	-
Water	124,225.5	164,801.7	12.4	2,484.4	-	-	12.4	12.4	-	828.1

Stream Number	SF-121	SF-122	SF-123	SF-124	SF-125	SF-126	SF-127	SF-128	SF-129	SF-130
Temperature (°F)	98.0	70.0	70.0	70.0	70.0	70.0	98.0	98.0	70.0	98.0
Pressure (psi)	16.2	14.7	14.7	14.7	14.7	14.7	14.7	16.2	14.7	14.7
Vapor Fraction	-	1.0	1.0	1.0	1.0	1.0	-	-	1.0	-
Mass (lb/hr)	845.1	134.1	0.7	134.1	134.1	134.1	169,010.0	169,010.0	134.1	31,689.4
Mole (lb-mol/hr)	46.7	4.6	0.0	4.6	4.6	4.6	9,330.5	9,330.5	4.6	1,749.5
Flow Time per batch (hr)	0.8	24.0	24.0	24.0	24.0	Continuous	0.8	0.8	Continuous	4.0
Volume (gpm)	0.2	224.4	1.1	1.1	224.4	224.4	42.3	42.3	224.4	7.9
State	Liquid	Vapor	Vapor	Vapor	Vapor	Vapor	Liquid	Liquid	Vapor	Liquid
Molar Components (lb-mol/hr)										
3-HP	-	-	-	-	-	-	-	-	-	-
Air	-	4.6	0.0	4.6	4.6	4.6	-	-	4.6	-
Biomass	0.7	-	-	-	-	-	139.1	139.1	-	26.1
Glucose	-	-	-	-	-	-	-	-	-	-
Media	-	-	-	-	-	-	-	-	-	-
Water	46.0	-	-	-	-	-	9,191.4	9,191.4	-	1,723.4
Mass Components (lb/hr)										
3-HP	-	-	-	-	-	-	-	-	-	-
Air	-	134.1	0.7	134.1	134.1	134.1	-	-	134.1	-
Biomass	16.9	-	-	-	-	-	3,380.2	3,380.2	-	633.8
Glucose	-	-	-	-	-	-	-	-	-	-
Media	-	-	-	-	-	-	-	-	-	-
Water	828.1	-	-	-	-	-	165,629.8	165,629.8	-	31,055.6

Table 5. Seed Fermentation Stream Table – Part 1

Stream Number	SF-131	SF-132	SF-133	SF-134	SF-137	SF-138	SF-139	SF-142	SF-143	SF-144
Temperature (°F)	70.0	98.0	98.0	97.0	98.0	98.0	97.0	98.0	98.0	97.0
Pressure (psi)	14.7	14.7	16.2	14.7	14.7	16.2	14.7	14.7	16.2	14.7
Vapor Fraction	1.0	-	-	-	-	-	-	-	-	-
Mass (lb/hr)	26,820.0	1,267.6	1,267.6	1,267.6	1,267.6	1,267.6	1,267.6	6.3	6.3	6.3
Mole (lb-mol/hr)	776,975.4	3,944.0	3,944.0	3,944.0	70.0	70.0	70.0	0.3	0.3	0.3
Flow Time per batch (hr)	Continuous	24.0	24.0	24.0	24.0	24.0	24.0	24.0	24.0	24.0
Volume (gpm)	44,886.0	0.3	0.3	0.3	0.3	0.3	0.3	0.0	0.0	0.0
State	Vapor	Liquid	Liquid	Liquid	Liquid	Liquid	Liquid	Liquid	Liquid	Liquid
Molar Components (lb-mol/hr)										
3-HP	-	-	-	-	-	-	-	-	-	-
Air	776,975.4	-	-	-	-	-	-	-	-	-
Biomass	-	-	-	-	1.0	1.0	1.0	0.0	0.0	0.0
Glucose	-	-	-	-	-	-	-	-	-	-
Media	-	-	-	-	-	-	-	-	-	-
Water	-	-	-	-	68.9	68.9	68.9	0.3	0.3	0.3
Mass Components (lb/hr)										
3-HP	-	-	-	-	-	-	-	-	-	-
Air	26,820.0	-	-	-	-	-	-	-	-	-
Biomass	-	25.4	25.4	25.4	25.4	25.4	25.4	0.1	0.1	0.1
Glucose	-	-	-	-	-	-	-	-	-	-
Media	-	-	-	-	-	-	-	-	-	-
Water	-	1,242.2	1,242.2	1,242.2	1,242.2	1,242.2	1,242.2	6.2	6.2	6.2

Table 6. Seed Fermentation Stream Table – Part 2

Section 3 – Process Fermentation

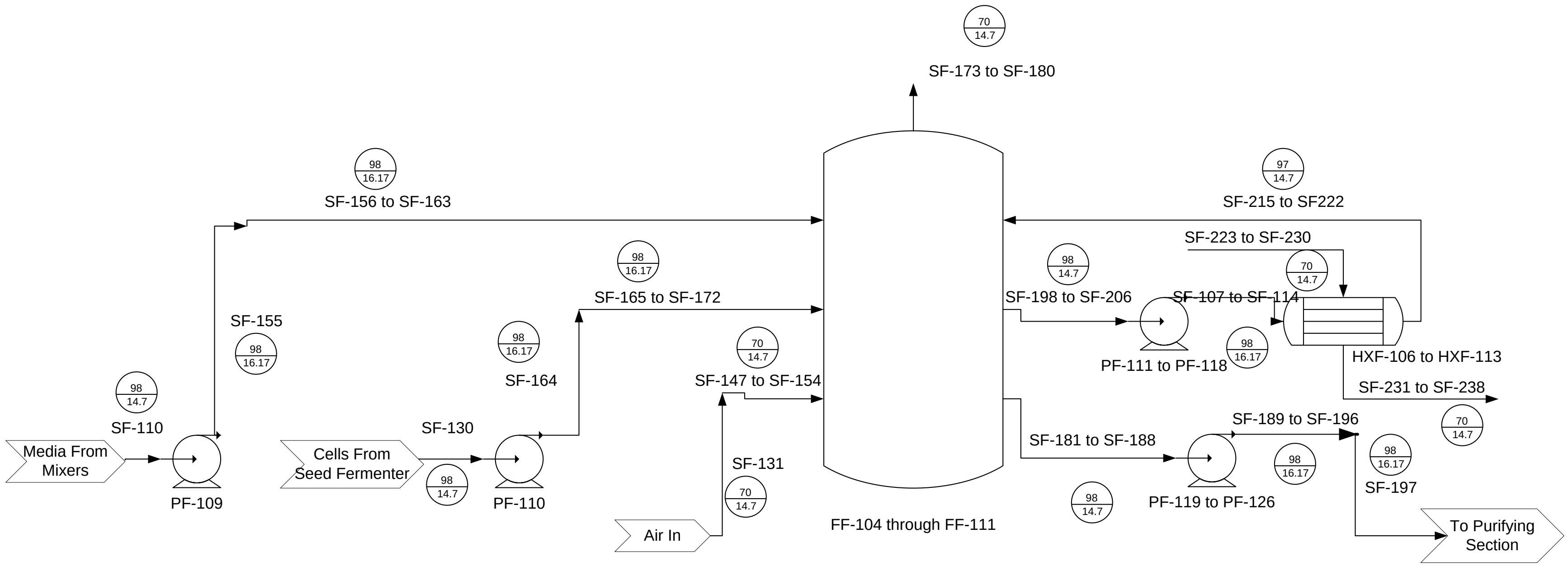

Figure 6. Process Fermentation Section Flowsheet

Stream Number	SF-110	SF-130	SF-131	SF-147 - SF-154	SF-155	SF-156 - SF-163	SF-164	SF-165 - SF-172	SF-173 - SF-180	SF-181 - SF-188
Temperature (°F)	98.0	98.0	70.0	70.0	98.0	98.0	98.0	98.0	70.0	98.0
Pressure (psi)	14.7	14.7	14.7	14.7	16.2	16.2	16.2	16.2	14.7	14.7
Vapor Fraction	-	-	1.0	1.0	-	-	-	-	1.0	-
Mass (lb/hr)	1,576,546.7	31,689.4	26,820.0	4,470.0	1,576,546.7	788,273.4	31,689.4	15,844.7	4,470.0	1,056,312.7
Mole (lb-mol/hr)	79,477.8	1,749.5	925.8	154.3	79,477.8	39,738.9	1,749.5	874.7	154.3	27,223.4
Flow Time per batch (hr)	16.0	4.0	Continuous	24.0	16.0	4.0	4.0	1.0	24.0	3.0
Volume (gpm)	1,577.2	7.9	44,886.0	7,481.0	1,577.2	788.6	7.9	4.0	7,481.0	1,056.7
State	Liquid	Liquid	Vapor	Vapor	Liquid	Liquid	Liquid	Liquid	Vapor	Liquid
Molar Components (lb-mol/hr)										
3-HP	-	-	-	-	-	-	-	-	-	479.0
Air	-	-	925.8	154.3	-	-	-	-	154.3	-
Biomass	-	26.1	-	-	-	-	26.1	13.0	-	434.7
Glucose	774.4	-	-	-	774.4	387.2	-	-	-	-
Media	205.0	-	-	-	205.0	102.5	-	-	-	-
Water	78,498.3	1,723.4	-	-	78,498.3	39,249.2	1,723.4	861.7	-	26,309.7
Mass Components (lb/hr)										
3-HP	-	-	-	-	-	-	-	-	-	86,983.9
Air	-	-	26,820.0	4,470.0	-	-	-	-	4,470.0	-
Biomass	-	633.8	-	-	-	-	633.8	316.9	-	21,126.3
Glucose	139,858.8	-	-	-	139,858.8	69,929.4	-	-	-	-
Media	22,148.0	-	-	-	22,148.0	11,074.0	-	-	-	-
Water	1,414,540.0	31,055.6	-	-	1,414,540.0	707,270.0	31,055.6	15,527.8	-	948,202.6

Stream Number	SF-189 - SF-196	SF-197	SF-198 - SF-206	SF-207 - SF-214	SF-215 - SF-222
Temperature (°F)	98.0	98.0	98.0	98.0	97.0
Pressure (psi)	16.2	16.2	14.7	16.2	14.7
Vapor Fraction	-	-	-	-	-
Mass (lb/hr)	1,056,312.7	2,112,625.4	31,689.4	31,689.4	31,689.4
Mole (lb-mol/hr)	27,223.4	108,893.6	1,589.6	1,589.6	1,589.6
Flow Time per batch (hr)	3.0	12.0	24.0	24.0	24.0
Volume (gpm)	1,056.7	4,226.9	31.5	31.5	31.5
State	Liquid	Liquid	Liquid	Liquid	Liquid
Molar Components (lb-mol/hr)	-	-	-	-	-
3-HP	479.0	1,915.9	28.7	28.7	28.7
Air	-	-	-	-	-
Biomass	434.7	1,738.8	26.1	26.1	26.1
Glucose	-	-	-	-	-
Media	-	-	-	-	-
Water	26,309.7	105,238.9	1,578.6	1,578.6	1,578.6
Mass Components (lb/hr)	-	-	-	-	-
3-HP	86,983.9	173,967.7	2,609.5	2,609.5	2,609.5
Air	-	-	-	-	-
Biomass	21,126.3	42,252.5	633.8	633.8	633.8
Glucose	-	-	-	-	-
Media	-	-	-	-	-
Water	948,202.6	1,896,405.2	28,446.1	28,446.1	28,446.1

Table 7. Process Fermentation Stream Table

Section 4 – Purifying Section

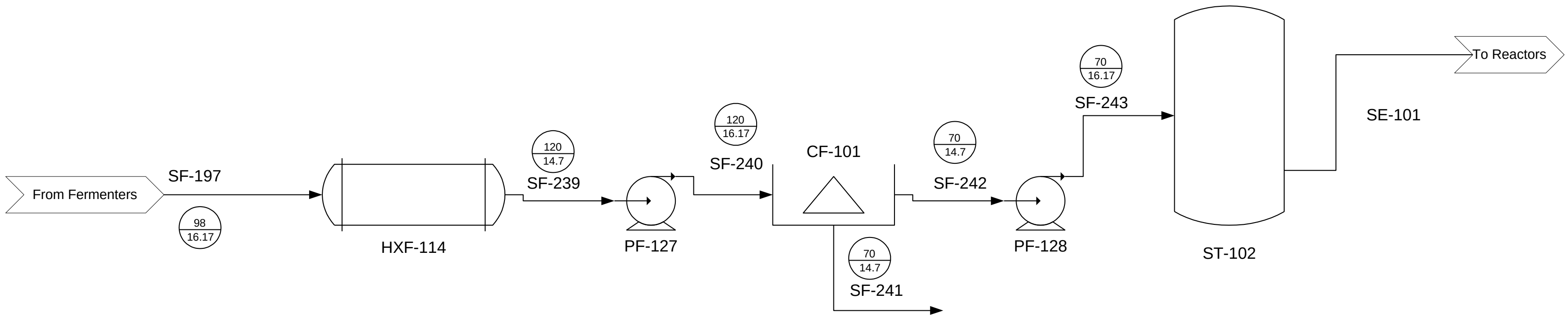

Figure 7. Purifying Section Flowsheet

Stream Number	SF-197	SF-239	SF-240	SF-241	SF-242	SF-243
Temperature (°F)	98.0	120.0	120.0	70.0	70.0	70.0
Pressure (psi)	16.2	14.7	16.2	14.7	14.7	16.2
Vapor Fraction	-	-	-	-	-	-
Mass (lb/hr)	2,112,625.4	2,112,625.4	2,112,625.4	231,893.0	1,880,732.4	1,880,732.4
Mole (lb-mol/hr)	108,893.6	108,893.6	108,893.6	12,262.7	96,631.0	96,631.0
Flow Time per batch (hr)	12.0	12.0	12.0	12.0	12.0	12.0
Volume (gpm)	4,226.9	4,226.9	4,226.9	464.0	3,763.0	3,763.0
State	Liquid	Liquid	Liquid	Liquid	Liquid	Liquid
Molar Components (lb-mol/hr)	-	-	-	-	-	-
3-HP	1,915.9	1,915.9	1,915.9	-	1,915.9	1,915.9
Air	-	-	-	-	-	-
Biomass	1,738.8	1,738.8	1,738.8	1,738.8	-	-
Glucose	-	-	-	-	-	-
Media	-	-	-	-	-	-
Water	105,238.9	105,238.9	105,238.9	10,523.9	94,715.0	94,715.0
Mass Components (lb/hr)	-	-	-	-	-	-
3-HP	173,967.7	173,967.7	173,967.7	-	173,967.7	173,967.7
Air	-	-	-	-	-	-
Biomass	42,252.5	42,252.5	42,252.5	42,252.5	-	-
Glucose	-	-	-	-	-	-
Media	-	-	-	-	-	-
Water	1,896,405.2	1,896,405.2	1,896,405.2	189,640.5	1,706,764.7	1,706,764.7

Table 8. Purification Section Stream Table

Section 5 – Evaporation Section

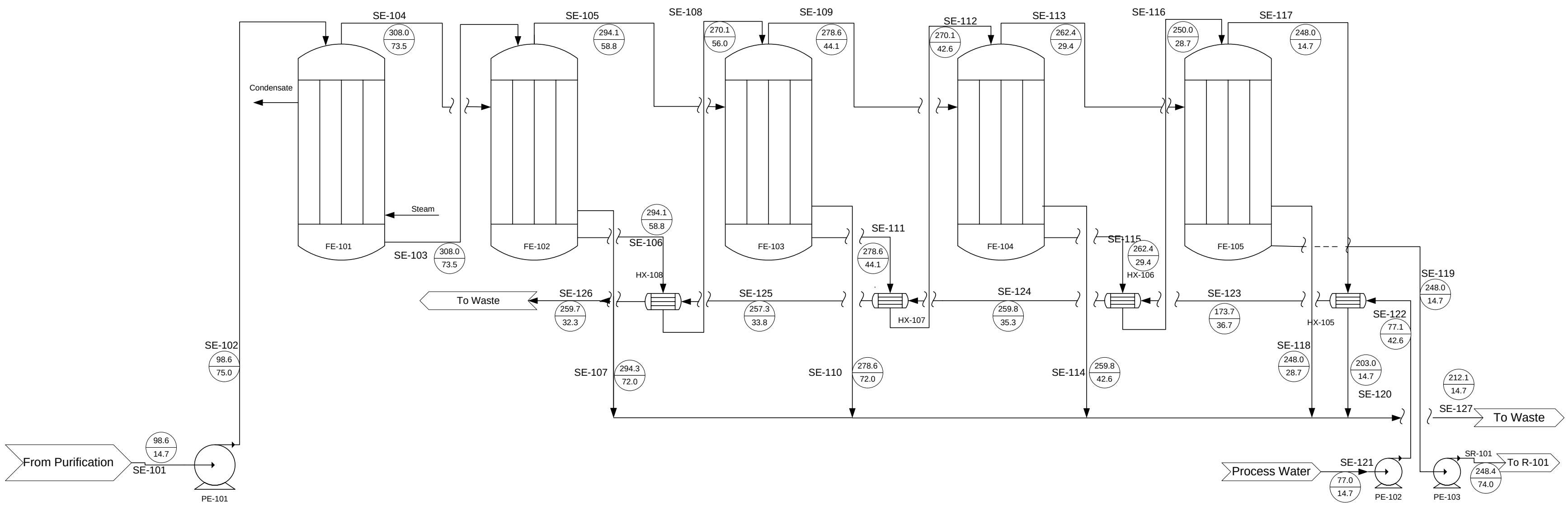

Figure 8. Evaporation Section Flowsheet

Stream Number	SE-101	SE-102	SE-103	SE-104	SE-105	SE-106	SE-107	SE-108	SE-109
Temperature (°F)	98.6	98.6	308.0	308.0	294.1	294.1	294.3	270.1	278.6
Pressure (psi)	14.7	75.0	73.5	73.5	58.8	58.8	72.0	56.0	44.1
Vapor Fraction	-	-	-	1.0	1.0	-	1.0	-	1.0
Mass (lb/hr)	728,165.5	728,165.5	534,988.6	193,172.3	204,020.8	330,967.8	193,172.3	330,967.8	163,835.8
Mole (lb-mol/hr)	37,429.0	37,429.0	26,746.6	10,682.1	11,268.2	15,478.4	10,682.1	15,478.4	9,023.7
Volume (gpm)	1,457.9	1,458.1	1,221.5	149,530.4	193,569.8	738.2	444.8	703.2	202,537.9
Density (lb/cuft)	62.4	62.4	54.7	0.2	0.1	56.0	54.2	58.8	0.1
State	Liquid	Liquid	Liquid	Vapor	Vapor	Liquid	Liquid	Liquid	Vapor
Molar Components (lb-mol/hr)									-
3-HP	747.8	747.8	737.6	10.1	14.2	723.4	10.1	723.4	17.7
Acrylic Acid	-	-	-	-	-	-	-	-	-
Carbon Dioxide	-	-	-	-	-	-	-	-	-
Phosphoric Acid	-	-	-	-	-	-	-	-	-
Water	36,681.3	36,681.3	26,009.0	10,672.0	11,254.0	14,755.0	10,672.0	14,755.0	9,006.0
Mass Components (lb/hr)									
3-HP	67,342.4	67,342.4	66,429.2	913.3	1,276.9	65,152.3	913.3	65,152.3	1,589.6
Acrylic Acid	-	-	-	-	-	-	-	-	-
Carbon Dioxide	-	-	-	-	-	-	-	-	-
Phosphoric Acid	-	-	-	-	-	-	-	-	-
Water	660,823.2	660,823.2	468,559.4	192,259.1	202,744.0	265,815.5	192,259.1	265,815.5	162,246.1

Stream Number	SE-110	SE-111	SE-112	SE-113	SE-114	SE-115	SE-116	SE-117	SE-118
Temperature (°F)	278.6	278.6	270.1	262.4	259.8	262.4	250.0	248.0	248.0
Pressure (psi)	72.0	44.1	42.6	29.4	42.6	29.4	28.7	14.7	28.7
Vapor Fraction	-	-	1.0	1.0	-	-	-	1.0	0.9
Mass (lb/hr)	204,020.8	167,128.7	167,128.7	30,040.8	163,835.8	91,139.7	91,139.7	21,614.5	75,989.0
Mole (lb-mol/hr)	11,268.2	6,454.6	6,454.6	1,612.8	9,023.7	2,291.2	2,291.2	1,166.8	4,163.3
Volume (gpm)	464.3	355.1	355.1	54,178.8	367.8	177.5	179.2	75,281.4	13,952.8
Density (lb/cuft)	54.9	58.8	58.8	0.1	55.6	64.1	63.5	0.0	0.7
State	Liquid	Liquid	Vapor	Vapor	Liquid	Liquid	Vapor	Vapor	Mixed
Molar Components (lb-mol/hr)									
3-HP	14.2	705.8	705.8	13.7	17.7	692.1	692.1	8.3	13.7
Acrylic Acid	-	-	-	-	-	-	-	-	-
Carbon Dioxide	-	-	-	-	-	-	-	-	-
Phosphoric Acid	-	-	-	-	-	-	-	-	-
Water	11,254.0	5,748.8	5,748.8	1,599.1	9,006.0	1,599.1	1,599.1	1,158.5	4,149.7
Mass Components (lb/hr)									
3-HP	1,276.9	63,562.7	63,562.7	1,231.9	1,589.6	62,330.8	62,330.8	743.5	1,231.9
Acrylic Acid	-	-	-	-	-	-	-	-	-
Carbon Dioxide	-	-	-	-	-	-	-	-	-
Phosphoric Acid	-	-	-	-	-	-	-	-	-
Water	202,744.0	103,566.0	103,566.0	28,808.9	162,246.1	28,808.9	28,808.9	20,871.1	74,757.1

Table 9. Evaporation Section Stream Table – Part 1

Stream Number	SE-119	SE-120	SE-121	SE-122	SE-123	SE-124	SE-125	SE-126	SE-127
Temperature (°F)	248.0	203.0	77.0	77.1	173.7	259.8	257.3	259.7	212.1
Pressure (psi)	14.7	14.7	14.7	42.6	36.7	35.3	33.8	32.3	14.7
Vapor Fraction	-	-	-	-	-	-	0.3	0.5	0.2
Mass (lb/hr)	69,525.2	21,614.5	227,082.6	227,082.6	227,082.6	227,082.6	227,082.6	227,082.6	658,646.8
Mole (lb-mol/hr)	1,124.5	1,166.8	12,605.0	12,605.0	12,605.0	12,605.0	12,605.0	12,605.0	36,304.9
Volume (gpm)	127.3	46.5	456.9	457.0	482.9	40,772.6	91,432.6	173,520.5	384,109.3
Density (lb/cuft)	68.2	58.0	62.1	62.0	58.7	0.7	0.3	0.2	0.2
State	Liquid	Liquid	Liquid	Liquid	Liquid	Liquid	Mixed	Mixed	Mixed
Molar Components (lb-mol/hr)									
3-HP	683.8	8.3	-	-	-	-	-	-	63.9
Acrylic Acid	-	-	-	-	-	-	-	-	-
Carbon Dioxide	-	-	-	-	-	-	-	-	-
Phosphoric Acid	-	-	-	-	-	-	-	-	-
Water	440.6	1,158.5	12,605.0	12,605.0	12,605.0	12,605.0	12,605.0	12,605.0	36,241.0
Mass Components (lb/hr)									
3-HP	61,587.3	743.5	-	-	-	-	-	-	5,755.1
Acrylic Acid	-	-	-	-	-	-	-	-	-
Carbon Dioxide	-	-	-	-	-	-	-	-	-
Phosphoric Acid	-	-	-	-	-	-	-	-	-
Water	7,937.9	20,871.1	227,082.6	227,082.6	227,082.6	227,082.6	227,082.6	227,082.6	652,891.8

Table 10. Evaporation Section Stream Table – Part 2

Section 6 – Reaction (Dehydration) Section

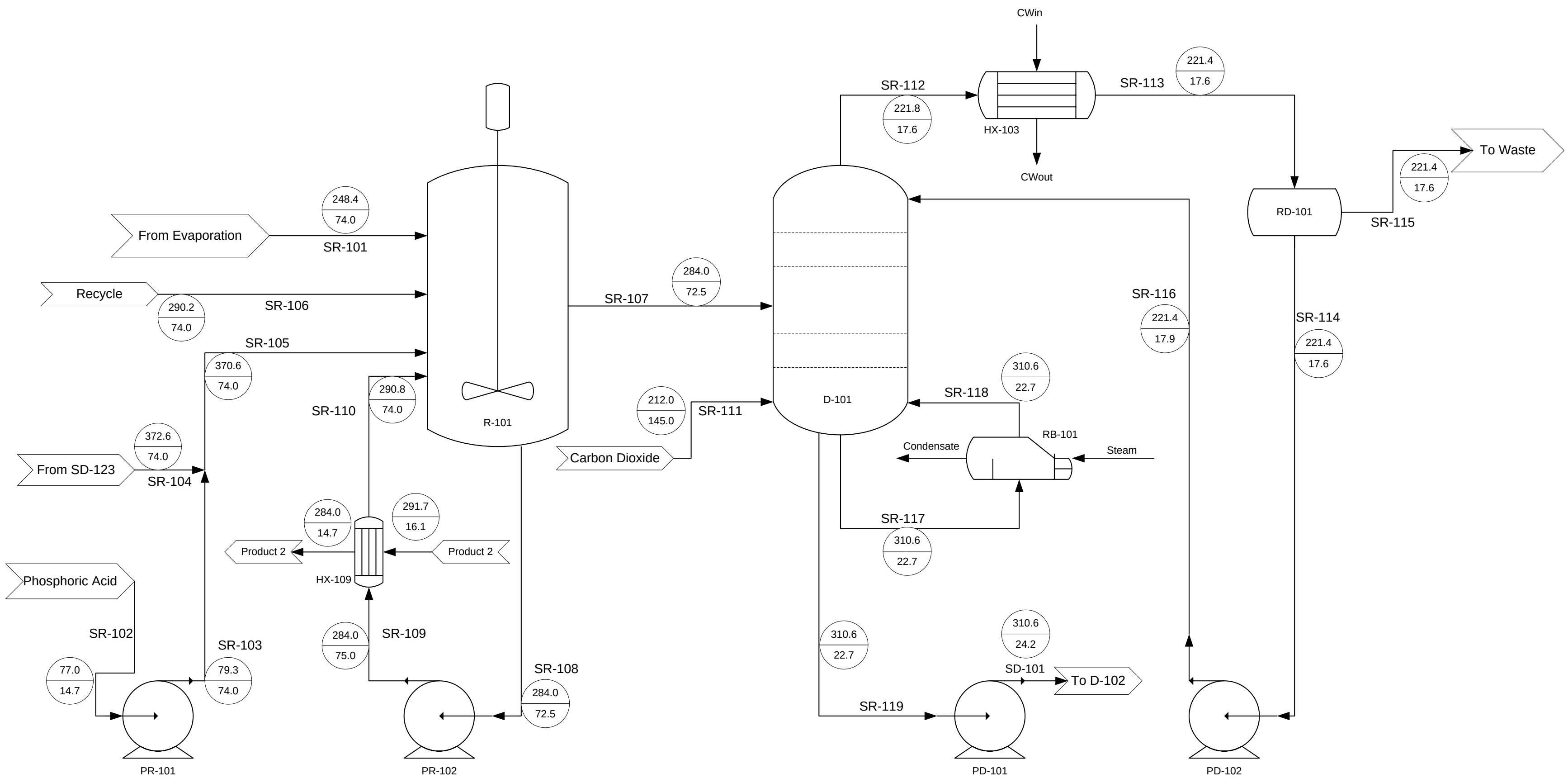

Figure 9. Reaction (Dehydration) Section

Stream Number	SR-101	SR-102	SR-103	SR-104	SR-105	SR-106	SR-107	SR-108	SR-109
Temperature (°F)	248.4	77.0	79.3	372.6	370.6	290.2	284.0	284.0	284.0
Pressure (psi)	74.0	14.7	74.0	74.0	74.0	74.0	72.5	75.0	75.3
Vapor Fraction	-	-	-	-	-	-	-	-	-
Mass (lb/hr)	69,525.2	22.1	22.1	3,121.5	3,143.5	410,920.4	483,570.0	48,357.0	48,357.0
Mole (lb-mol/hr)	1,124.5	0.2	0.2	34.8	35.0	5,739.2	7,104.2	710.4	710.4
Volume (gpm)	127.3	0.1	0.1	9.4	9.4	909.5	1,051.0	105.4	103.1
Density (lb/cuft)	68.2	37.9	37.9	41.6	41.5	56.4	57.4	57.3	58.6
State	Liquid	Liquid	Liquid	Liquid	Liquid	Liquid	Liquid	Liquid	Liquid
Molar Components (lb-mol/hr)									
3-HP	683.8	-	-	2.2	2.2	0.0	480.2	48.0	48.0
Acrylic Acid	-	-	-	10.3	10.3	5,690.2	5,906.0	590.6	590.6
Carbon Dioxide	-	-	-	-	-	0.0	0.0	0.0	0.0
Phosphoric Acid	-	0.2	0.2	22.3	22.5	-	22.5	2.2	2.2
Water	440.6	-	-	-	-	49.0	695.5	69.6	69.6
Mass Components (lb/hr)									
3-HP	61,587.3	-	-	196.9	196.9	0.0	43,248.7	4,324.9	4,324.9
Acrylic Acid	-	-	-	741.9	741.9	410,037.4	425,586.8	42,558.7	42,558.7
Carbon Dioxide	-	-	-	-	-	0.0	0.0	0.0	0.0
Phosphoric Acid	-	22.1	22.1	2,182.6	2,204.7	-	2,204.7	220.5	220.5
Water	7,937.9	-	-	-	-	883.0	12,529.7	1,253.0	1,253.0

Stream Number	SR-110	SR-111	SR-112	SR-113	SR-114	SR-115	SR-116	SR-117	SR-118	SR-119
Temperature (°F)	290.8	212.0	221.8	221.4	221.4	221.4	221.4	310.6	310.6	310.6
Pressure (psi)	74.0	145.0	17.6	17.6	17.6	17.6	17.9	22.7	22.7	22.7
Vapor Fraction	-	1.0	1.0	0.2	-	1.0	-	-	1.0	-
Mass (lb/hr)	48,357.0	2.2	129,774.4	129,774.4	108,305.7	21,468.7	107,772.7	462,110.8	462,110.8	462,110.8
Mole (lb-mol/hr)	710.4	0.1	6,875.2	6,875.2	5,734.3	1,140.9	5,727.2	6,441.3	6,441.3	6,441.3
Volume (gpm)	103.6	0.3	352,249.3	284.4	235.4	59,040.4	234.4	1,040.9	1,521.8	1,041.0
Density (lb/cuft)	58.3	0.9	0.0	57.0	57.4	0.0	57.4	55.4	37.9	55.4
State	Liquid	Vapor	Vapor	Mixed	Liquid	Vapor	Liquid	Liquid	Vapor	Liquid
Molar Components (lb-mol/hr)										
3-HP	48.0	-	-	-	-	-	-	2.2	2.2	2.2
Acrylic Acid	590.6	-	109.3	109.3	92.4	16.9	84.9	6,367.1	6,367.1	6,367.1
Carbon Dioxide	0.0	0.1	0.3	0.3	0.3	0.1	0.3	0.0	0.0	0.0
Phosphoric Acid	2.2	-	-	-	-	-	-	22.5	22.5	22.5
Water	69.6	-	6,765.6	6,765.6	5,641.6	1,124.0	5,642.1	49.5	49.5	49.5
Mass Components (lb/hr)										
3-HP	4,324.9	-	-	-	-	-	-	199.1	199.1	199.1
Acrylic Acid	42,558.7	-	7,876.7	7,876.7	6,659.5	1,217.2	6,118.1	458,815.0	458,815.0	458,815.0
Carbon Dioxide	0.0	2.2	13.3	13.3	11.1	2.2	11.1	0.0	0.0	0.0
Phosphoric Acid	220.5	-	-	-	-	-	-	2,204.7	2,204.7	2,204.7
Water	1,253.0	-	121,884.4	121,884.4	101,635.1	20,249.3	101,643.6	891.9	891.9	891.9

Table 11. Reaction (Dehydration) Section Stream Table

Section 7 – Distillation (Purification) Section

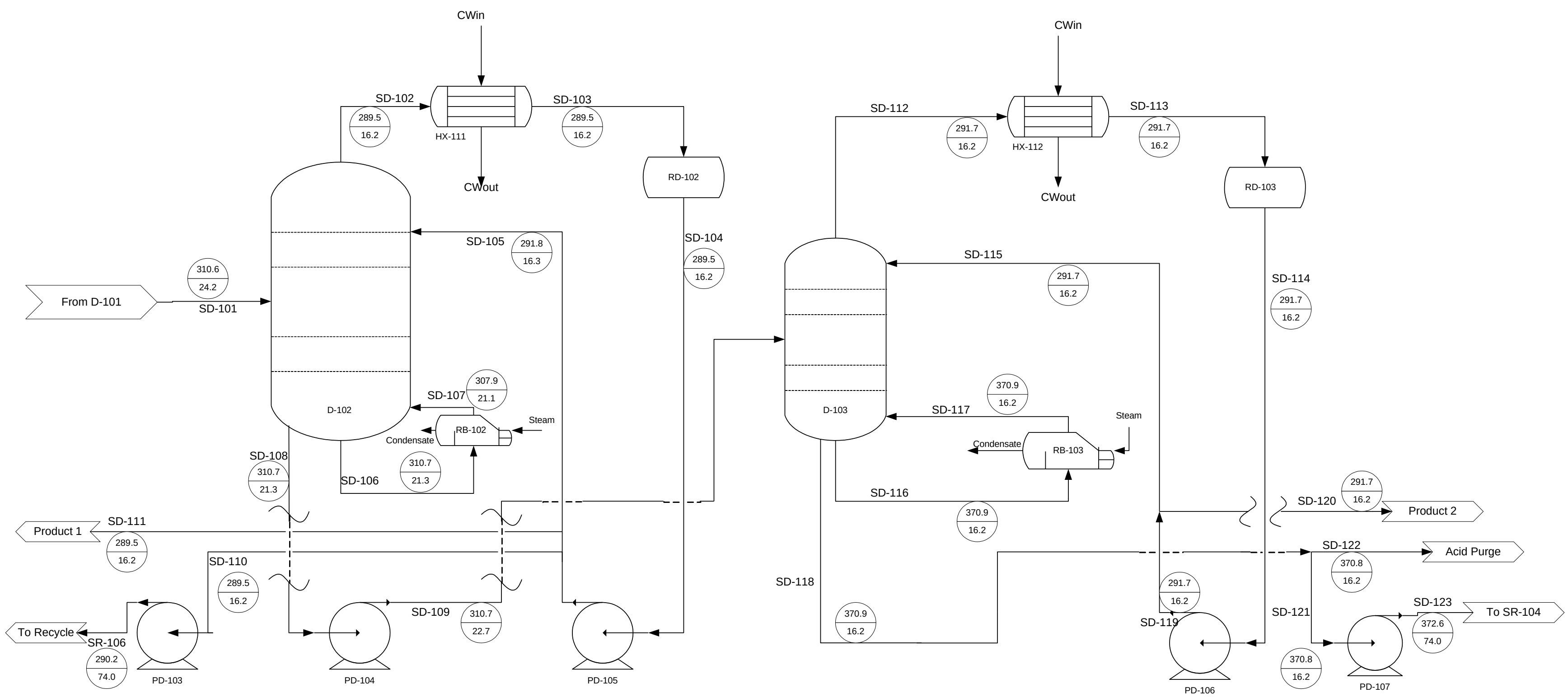

Figure 10. Distillation (Purification) Section

Stream Number	SD-101	SD-102	SD-103	SD-104	SD-105	SD-106	SD-107	SD-108	SD-109
Temperature (°F)	310.6	289.5	289.5	289.5	291.8	310.7	307.9	310.7	310.7
Pressure (psi)	24.2	16.2	16.2	16.2	16.3	21.3	21.1	21.3	22.7
Vapor Fraction	-	1.0	-	-	-	-	1.0	-	-
Mass (lb/hr)	462,110.8	2,490,048.9	2,490,048.9	2,490,048.9	2,074,977.8	47,039.7	47,039.7	47,039.7	47,036.4
Mole (lb-mol/hr)	6,441.3	35,815.5	35,815.5	35,815.5	30,018.3	644.1	644.1	644.1	644.1
Volume (gpm)	1,041.0	2,114,995.5	5,507.6	5,507.6	4,591.2	106.7	106.7	106.6	31,745.4
Density (lb/cuft)	55.4	0.1	56.5	56.5	56.4	55.1	55.1	55.1	0.2
State	Liquid	Vapor	Liquid	Liquid	Liquid	Liquid	Vapor	Liquid	Vapor
Molar Components (lb-mol/hr)									
3-HP	2.2	-	-	-	-	2.2	2.2	2.2	2.2
Acrylic Acid	6,367.1	34,135.1	34,135.1	34,135.1	28,387.4	619.4	619.4	619.4	619.4
Carbon Dioxide	0.0	-	-	-	-	-	-	-	-
Phosphoric Acid	22.5	-	-	-	-	22.5	22.5	22.5	22.5
Water	49.5	1,680.4	1,680.4	1,680.4	1,630.9	0.0	0.0	0.0	0.0
Mass Components (lb/hr)									
3-HP	199.1	-	-	-	-	199.1	199.1	199.1	198.9
Acrylic Acid	458,815.0	2,459,776.7	2,459,776.7	2,459,776.7	2,045,597.5	44,635.9	44,635.9	44,635.9	44,633.3
Carbon Dioxide	-	-	-	-	-	-	-	-	-
Phosphoric Acid	2,204.7	-	-	-	-	2,204.7	2,204.7	2,204.7	2,204.2
Water	891.9	30,272.2	30,272.2	30,272.2	29,380.3	0.0	0.0	0.0	0.0

Stream Number	SD-110	SD-111	SD-112	SD-113	SD-114	SD-115	SD-116	SD-117	SD-118
Temperature (°F)	289.5	289.5	291.7	291.7	291.7	291.7	370.9	370.9	370.8
Pressure (psi)	16.2	16.2	16.2	16.2	16.2	16.2	16.2	16.2	16.2
Vapor Fraction	-	-	1.0	-	-	-	-	1.0	-
Mass (lb/hr)	410,920.4	4,150.7	131,663.9	131,659.6	131,659.6	87,773.0	3,153.0	3,153.0	3,148.7
Mole (lb-mol/hr)	5,739.2	56.4	1,827.1	1,827.1	1,827.1	1,218.1	35.1	35.1	35.0
Volume (gpm)	909.0	8.4	114,162.4	291.7	291.7	194.5	9.5	3,005.2	9.5
Density (lb/cuft)	56.4	62.1	0.1	56.4	56.4	56.4	41.6	0.1	41.6
State	Liquid	Liquid	Vapor	Liquid	Liquid	Liquid	Liquid	Vapor	Liquid
Molar Components (lb-mol/hr)									
3-HP	0.0	0.0	-	0.0	0.0	0.0	2.2	2.2	2.2
Acrylic Acid	5,690.2	57.5	1,827.1	1,827.1	1,827.1	1,218.1	10.4	10.4	10.3
Carbon Dioxide	0.0	0.0	-	-	-	-	-	-	-
Phosphoric Acid	-	-	-	-	-	-	22.5	22.5	22.5
Water	49.0	0.5	-	-	-	-	-	-	-
Mass Components (lb/hr)									
3-HP	0.0	0.0	-	0.2	0.2	0.2	198.9	198.9	198.9
Acrylic Acid	410,037.4	4,141.8	131,663.9	131,659.3	131,659.3	87,772.9	749.4	749.4	745.6
Carbon Dioxide	0.0	0.0	-	-	-	-	-	-	-
Phosphoric Acid	-	-	-	-	-	-	2,204.7	2,204.7	2,204.2
Water	883.0	8.9	-	-	-	-	-	-	-

Table 12. Distillation (Purification) Section Stream Table – Part 1

Stream Number	SD-119	SD-120	SD-121	SD-122	SD-123
Temperature (°F)	291.7	291.7	370.8	370.8	372.6
Pressure (psi)	16.2	16.2	16.2	16.2	74.0
Vapor Fraction	-	-	-	-	-
Mass (lb/hr)	131,659.6	43,886.5	3,121.5	31.5	3,121.5
Mole (lb-mol/hr)	1,827.1	609.0	34.8	0.4	34.8
Volume (gpm)	291.7	97.2	9.4	0.1	9.4
Density (lb/cuft)	56.4	56.4	41.6	41.6	41.6
State	Liquid	Liquid	Liquid	Liquid	Liquid
Molar Components (lb-mol/hr)					
3-HP	0.0	0.0	2.2	0.0	2.2
Acrylic Acid	1,827.1	609.0	10.3	0.1	10.3
Carbon Dioxide	-	-	-	-	-
Phosphoric Acid	-	-	22.3	0.2	22.3
Water	-	-	-	-	-
Mass Components (lb/hr)					
3-HP	0.2	0.1	196.9	2.0	196.9
Acrylic Acid	131,659.3	43,886.4	741.9	7.5	741.9
Carbon Dioxide	-	-	-	-	-
Phosphoric Acid	-	-	2,182.6	22.1	2,182.6
Water	-	-	-	-	-

Table 13. Distillation (Purification) Section Stream Table – Part 2

Process Description

Preparation of Glucose Feed

This report compares two different sources of glucose: corn and sugarcane. Depending on the sugar source that is chosen based on economic considerations, the preparation of the glucose feed section differs.

The glucose product from corn is a corn mash that is an intermediate in the beginning sections of the ethanol fermentation process. Studies have indicated that corn consists of 82% glucose[6]. Since corn is often used as a feed for ethanol production, the machinery and required reactants to convert the corn into corn mash is well documented. The corn is first cleaned before entering a hammer mill where it is mashed. After passing through a weighing tank, it enters a slurry mix where ammonia, lime, and a-amylase are added. This mix then undergoes liquefaction before it is heated in cook retention tanks and undergoes saccharification[7]. The corn mash solution produced following saccharification is the desired product from this process. The average ethanol plant produces 65 million gallons of ethanol per year and consumes 23 million bushels of corn annually[8]. Since the plant suggested in this report intends to consume approximately 9 million bushels of corn annually, a typical plant controlled by the chosen corn mash supplier would easily be able to produce that amount of glucose necessary for this process.

Similarly, sugarcane is another major raw material that is chosen as a source for ethanol production. In sugarcane processing, there are two major byproducts that can be used as feed material for acrylic acid production; molasses and cane juice. Sugarcane processing begins with the raw sugarcane stalks entering mills with water. Here, unpurified sugarcane juice is separated from the bagasse, which are the fibers and similar materials that are left after squeezing the juice

[6] [14] Dale
[7] [28] Kwiatowski
[8] [47] Urbanchuk

from the sugarcane stalks. This unpurified juice then undergoes liming where lime and heat are added to neutralize organic acids and cause a precipitate to form. This precipitate waste, called "mud", can be removed via centrifugation. The remaining sugar solution is then sent to a flash distillation and a settler where any remaining mud and air are removed resulting in a clarified juice[9]. This juice is the product that would be used as the glucose source for the designed acrylic acid producing process.

Molasses, another derivative of sugarcane, has a higher sugar content, approximately 46%[10], but it also takes far more processing and requires more raw materials to produce, resulting in a higher input and processing costs. The average sugarcane processing plant in Brazil processes 2 million tons of sugarcane per year[11]. Assuming that sugarcane consists of 9% usable sugar[12], approximately 1.2 million tons per year of sugarcane are needed to meet the minimum amount of feedstock needed for the plant designed in this report. As such, a typical sugarcane processing plant should be able to produce the feedstock needed for the plant.

This report does not explicitly show the process of deriving glucose from corn or sugarcane but assumes a pure glucose feed that is priced at the market price of corn or sugarcane.

Section 1 - Fermentation Process

The first section explicitly designed in this report is the batch fermentation of genetically engineered *E. coli* that converts glucose to 3-HP. This process begins with water and nutrient media feed streams being combined in a large mixer (MF-101). The nutrient media feed consists of yeast extract and various salts that are required for bacterial growth. This mixture of water

[9] [16] Dias
[10] [12] Curtin
[11] [15] De Almeida
[12] [4] Almazan

and nutrients is then sterilized in HXF-101. Part of the exit stream is then sent to a second mixer (MF-102) where it is combined with the glucose feed which has also been sterilized. The final mixture from SF-110 consists of 10% glucose, 2% nutrients and the rest water. Higher glucose levels have an inhibitory effect on *E. coli* growth and decreases the rate of 3-HP production.

The remaining portion of the water and media stream (SF-106) from the first mixer is sent to fill three seed fermenters. These seed fermenters are used in series to aerobically grow a 1.5 mL inoculum of *E. coli* cells into a culture large enough to produce the desired quantity of 3-HP. The seed fermenters, which increase their volume in series by 200x each, are necessary because such a small culture of *E. coli* cells would not be able to grow successfully in the large fermenters used to produce the 3-HP. The seed fermenters are airlift fermenters which use a feed stream of filtered air to agitate the contents of the vessel as well as provide the oxygen necessary for aerobic growth. Each seed fermenter cultures the *E. coli* for 24 hours at 98^{o}F. The product from the final seed fermenter is sent to a storage vessel which holds the product until it is needed in the following fermentation section. The seed fermenter product is 98% water and 2% biomass (this process assumes that the nutrients are entirely consumed by the *E. coli* and converted into biomass).

Following the seed fermenters, the *E. coli* culture is split and sent to one of eight fermenters. These are each 425,000 gallon airlift fermenters. They are simultaneously filled with the 10% glucose solution created previously in the second mixer. The filling of these fermenters is staggered so that two are filled every six hours. This helps to reduce the size of the mixers and pumps necessary for this process. The *E. coli* is again fermented for 24 hours and converts the glucose into 3-HP. Each fermenter is then completely drained and cleaned before being used in the next batch, using CIP and SIP systems. The exit fluid contains 9.25% 3-HP, 2% biomass, 88.75% water, and negligible amounts of glucose and the media nutrients.

Following fermentation the exit flow is pumped through a heat exchanger which heats the liquid to 248°F to kill the *E. coli* cells. The dead cell mass is then removed using a centrifuge. The remaining water and 3-HP product is then stored in a storage tank that can be drawn from continuously in the reaction part of the 3-HP to acrylic acid process.

The diagram below shows the scheduling for this process. The large fermenters are the bottleneck unit for this process. Fermentation time is 24 hours and total batch time is 31 hours. Detailed scheduling analysis can be found in Appendix III - Batch Process Scheduling, on page 228 of the design report.

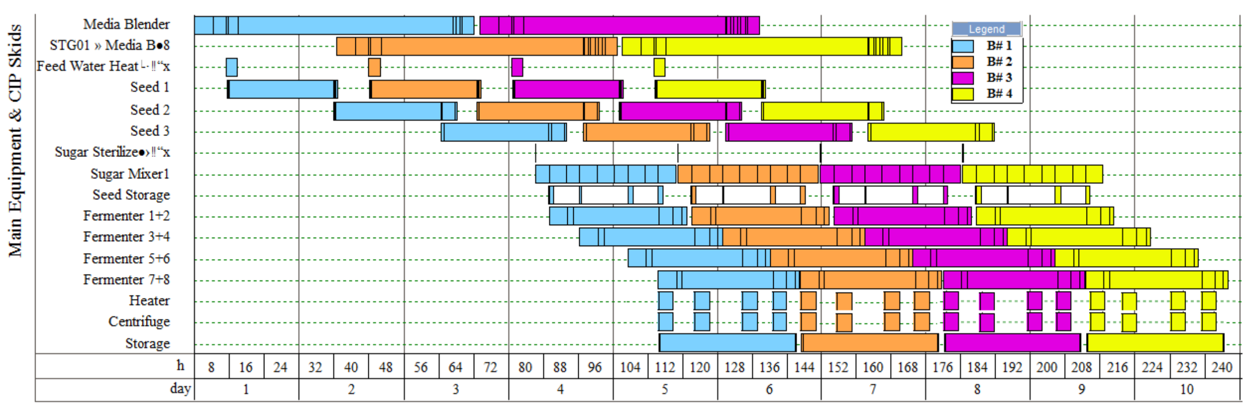

Figure 11. Gantt Chart – Fermentation Process

Section 2 – Reaction (Dehydration)

The conversion from 3-HP to acrylic acid is the following dehydration reaction:

3-HP → Acrylic Acid + H2O (in the presence of phosphoric acid catalyst)

3-HP solution from the fermentation process enters this stage of the process and is continuously pumped into the first of a series of flash vessels. The purpose of the flash vessel evaporation process is to remove the large amounts of excess water in the fermentation product while retaining the 3-HP within the solution. This greatly reduces the size of the downstream equipment needed because of the water that is a product of the dehydration reaction. The solution enters this series of flash vessels at 98.6ºF and 14.7 psi with a composition of 90.75% water and 9.25% 3-HP by weight. It leaves this process at a temperature of 248ºF and 74 psi with a composition of 11.5% water and 88.5% 3-HP, retaining 91.4% of the 3-HP while removing nearly 98.8% of the water.

This solution of water and 3-HP is then brought into a continuous stirred tank reactor where the phosphoric acid catalyst is added and 29.8% of the 3-HP is converted into acrylic acid. The reactor contents are then pumped to a 35-stage reactive distillation tower where the remaining 3-HP is converted into acrylic acid, bringing the overall conversion at this point to 99.7%. From this first distillation tower, a large amount of water is removed in the overhead product. A stream containing 99.2% acrylic acid by weight flows out of the bottoms. There is a constant pressure of carbon dioxide applied to the distillation tower to prevent decarboxylation side reactions. According to pertinent patents, an atmosphere of at least 50% CO_2 functionally prevents decarboxylation in the distillation column, and only trace amounts of decarboxylation products are present.[13] Since the proposed process takes the application of carbon dioxide to the column into account, the trace side reactions are ignored for modeling simplicity.

Section 3 – Distillation (Purification)

This highly concentrated acrylic acid stream is then sent to a second 35-stage distillation tower. .17% of the acrylic acid-rich overheads is removed as product and the rest is recycled into the top-tray of the distillation column. The bottoms stream contains 94.8% acrylic acid, 4.7% phosphoric acid and the remaining 3-HP. This stream is then pumped to a final 5-stage distillation tower where the acrylic acid is removed in the overheads and collected as product. The bottoms contains phosphoric acid and 3-HP. 99% of this stream is recycled back to the initial CSTR, while the remainder is purged.

The overhead from the third distillation tower is combined with the overhead from the second tower to create the final product stream. The overall conversion of 3-HP to acrylic acid is 99.7%. Of this, 97.5% of the acrylic acid is retained in the final product producing a 99.99% pure stream being produced at a rate of 48,037.2lb/hr (105.6 gpm).

[13] [19] Gokarn

Energy Balance and Utility Requirements

Energy Balance

Process Energy Requirements

Equipment	Description	Duty (BTU/hr)	Source	Notes
Mixing Section				
MF-101	Media Mixing Tank	953,775	Electricity	Agitation of Media and Water
MF-102	Glucose Mixing Tank	1,505,311	Electricity	Agitation of Glucose, Media and Water Mixture
PF-101	Pump	524,446	Electricity	Pump Media Mixture to HXF-101
HXF-101	Heat Exchanger	196,373,516	Steam (50 psig)	Sterilize Media Mixture
HXF-102	Heat Exchanger	6,113,678	Steam (50 psig)	Sterilize Glucose Mixture before Mixing with Media
Total		**205,470,725**		
Seed Fermentation Section				
AF-101	Air Filter	-		
PF-102	Pump	84,962	Electricity	Pump Media Mixture to Seed Fermenters
PF-103	Pump	3,740	Electricity	Pump Inoculum from FF-101 to FF-102
PF-104	Pump	2,036	Electricity	Pump FF-101 contents to HXF-103
PF-105	Pump	38,675	Electricity	Pump Inoculum from FF-102 to FF-103
PF-106	Pump	3,706	Electricity	Pump FF-102 contents to HXF-104
PF-107	Pump	53,912	Electricity	Pump Inoculum from FF-103 to STF-101
PF-108	Pump	3,740	Electricity	Pump FF-103 contents to HXF-105
HXF-103	Heat Exchanger	(5)	Cooling Water	Cool FF-101 contents
HXF-104	Heat Exchanger	(986)	Cooling Water	Cool FF-102 contents
HXF-105	Heat Exchanger	(986)	Cooling Water	Cool FF-103 contents
Total		**188,796**		
Fermentation Section				
PF-109	Pump	63,125	Electricity	Pump Media Mixture to Fermenters
PF-110	Pump	13,898	Electricity	Pump Inoculum from Seed Fermenters to Fermenters
PF-111	Pump	1,747,151	Electricity	Pump Fermenter contents to Heat Exchangers
PF-112	Pump	1,747,151	Electricity	Pump Fermenter contents to Heat Exchangers
PF-113	Pump	1,747,151	Electricity	Pump Fermenter contents to Heat Exchangers
PF-114	Pump	1,747,151	Electricity	Pump Fermenter contents to Heat Exchangers
PF-115	Pump	1,747,151	Electricity	Pump Fermenter contents to Heat Exchangers
PF-116	Pump	1,747,151	Electricity	Pump Fermenter contents to Heat Exchangers
PF-117	Pump	1,747,151	Electricity	Pump Fermenter contents to Heat Exchangers
PF-118	Pump	1,747,151	Electricity	Pump Fermenter contents to Heat Exchangers
HXF-106	Heat Exchanger	24,639	Cooling Water	Cool Fermenter Contents
HXF-107	Heat Exchanger	24,639	Cooling Water	Cool Fermenter Contents
HXF-108	Heat Exchanger	24,639	Cooling Water	Cool Fermenter Contents
HXF-109	Heat Exchanger	24,639	Cooling Water	Cool Fermenter Contents
HXF-110	Heat Exchanger	24,639	Cooling Water	Cool Fermenter Contents
HXF-111	Heat Exchanger	24,639	Cooling Water	Cool Fermenter Contents
HXF-112	Heat Exchanger	24,639	Cooling Water	Cool Fermenter Contents
HXF-113	Heat Exchanger	24,639	Cooling Water	Cool Fermenter Contents
PF-119	Pump	1,146,479	Electricity	Pump Fermentation Product to Purifying Section
PF-120	Pump	1,146,479	Electricity	Pump Fermentation Product to Purifying Section
PF-121	Pump	1,146,479	Electricity	Pump Fermentation Product to Purifying Section
PF-122	Pump	1,146,479	Electricity	Pump Fermentation Product to Purifying Section
PF-123	Pump	1,146,479	Electricity	Pump Fermentation Product to Purifying Section
PF-124	Pump	1,146,479	Electricity	Pump Fermentation Product to Purifying Section
PF-125	Pump	1,146,479	Electricity	Pump Fermentation Product to Purifying Section
PF-126	Pump	1,146,479	Electricity	Pump Fermentation Product to Purifying Section
Total		**23,423,178**		

Process Energy Requirements				
Equipment	Description	Duty (BTU/hr)	Source	Notes
Purifying Section				
HXF-114	Heat Exchanger	36,137,563	Steam (50 psig)	Sterilize Fermentation Product (120 ˚F)
PF-127	Pump	423,105	Electricity	Pump Sterilized Product to Centrifuge
CF-101	Centrifuge	4,837,890	Electricity	Separate Biomass and Fermentation Broth
PF-128	Pump	819,926.36	Electricity	Pump Separated Fermentation Product to ST-102
Total		**42,218,484**		
Evaporation Section				
PE-101	Pump	163,373	Electricity	Pump Fermentation Product to FE-101 at 75 psi
FE-101	Flash Vessel	331,217,356	Steam (150 psig)	Partially vaporize fermentation product at 308˚F and 73.5 psi
HX-105	Heat Exchanger	(21,144,209)	Cooling Water	Cool bottoms product of FE-102
HX-106	Heat Exchanger	(46,157,813)	Cooling Water	Cool bottoms product of FE-103
HX-107	Heat Exchanger	(86,796,853)	Cooling Water	Cool bottoms product of FE-104
HX-108	Heat Exchanger	(44,548,041)	Cooling Water	Condense vapor product of FE-105
PE-102	Pump	26,819	Electricity	Pump cooling water to HX-105
PE-103	Pump	19,756	Electricity	Pump FE-105 bottoms to Reaction Section
Total		**132,780,389**		
Reaction Section				
PR-101	Pump	20	Electricity	Pump Phosphoric Acid to Reactor Vessel
R-101	Reaction Vessel	24,288	Electricity	Agitated Reactor Vessel
PR-102	Pump	10,202	Electricity	Pump Reactor Contents to HX-109
HX-109	Heat Exchanger	111,443	Product Stream	Heat Reactor Contents with Product Stream
HX-103	Condenser	(98,893,879)	Cooling Water	Total Condenser of D-101 Vapor Product
PD-101	Pump	2,931	Electricity	D-101 Reflux Pump
PD-102	Pump	143,651	Electricity	Pump Bottoms Product to Distillation Section
RB-101	Reboiler	127,030,055	Steam (150 psig)	Vaporize D-101 bottoms contents
Total		**28,428,711**		
Distillation Section				
PD-103	Pump	102,023	Electricity	Pump Product to Reaction Section
PD-104	Pump	427	Electricity	Pump Bottoms of D-102 to D-103
PD-105	Pump	78,369	Electricity	D-102 Reflux Pump
PD-106	Pump	105,848	Electricity	D-103 Reflux Pump
PD-107	Pump	2,501	Electricity	Pump Acid Recycle to Reaction Section
HX-111	Condenser	(428,205,936)	Cooling Water	Total Condenser of D-102 Vapor Product
HX-112	Condenser	(22,309,423)	Cooling Water	Total Condenser of D-103 Vapor Product
RB-102	Reboiler	425,220,615	Steam (150 psig)	Vaporize D-102 bottoms contents
RB-103	Reboiler	22,123,352	Steam (150 psig)	Vaporize D-103 bottoms contents
Total		**(2,882,224)**		
Total Process Energy Requirement		**429,628,060**		

Table 14. Process Energy Requirements

Energy requirements for the process are calculated for each unit based on the specific requirements for each process unit. Steam, cooling water and electricity requirement calculations are shown in Appendix IV - Design Calculations on page 236 of the design report. As seen in Table 14, the most energy intensive processes are in the mixing section and evaporation sections.

This is due to the large steam requirements needed to sterilize and mix the growth nutrient media used in the fermentation (due to high amounts of water) and then the high amount of steam needed to drive the evaporation separation after the purification of the fermentation product (again due to the large amount of water in the process). The fermentation, purifying and reaction sections of the process have comparatively lower energy requirements and are simply due to the scale of the proposed design, which carries significant amounts of flow through the process and therefore have significant electricity requirements for pumps.

It is important to note that the proposed process eliminates the need for agitation within the process fermenters by assuming that sufficient agitation and aeration is provided by the airlift design shown in Figure 2. Airlift Fermenter Schematic to have the fermentation operate at the targeted aerobic yields. If the agitation provided is not sufficient for this purpose, manual agitation by impellers may be necessary for the fermenters and could significantly increase the electricity requirements of the process, as well as the capital investment required for the impellers and associated infrastructure in the fermenters. This would adversely affect the profitability of the process, but could be adequately explored on laboratory scale to ensure that airlift fermenters deliver proper levels of aeration.

The overall process utility requirements, organized by utility type are shown explicitly in Table 15, Table 16, Table 17 and Table 18.

Utility Requirements

50 psi Steam		
Process Unit	Heating Duty (BTU/hr)	Amount (lb/hr)
HXF-114	36,137,563	50,192
HXF-101	196,373,516	276,167
HXF-102	6,113,678	7,533
Total	**238,624,756**	**333,892**

Table 15. 50 psi Steam

150 psi Steam		
Process Unit	Heat Duty (BTU/hr)	Amount (lb/hr)
FE-101	331,217,356	383,442
RB-101	127,030,055	146,213
RB-102	425,220,615	489,434
RB-103	22,123,352	25,464
Total	**905,591,378**	**1,044,554**

Table 16. 150 psi Steam

Cooling Water		
Process Unit	Required Cooling Duty (BTU/hr)	Amount of Cooling Water Required (lb/hr)
HX-111	428,205,936	14,273,531
HX-103	98,893,879	21,469
HX-112	22,309,423	43,887
HXF-104	1,268	254
HXF-105	1,268	254
HXF-106 to HXF-113	253,515	50,703
Total	**549,665,288**	**14,390,097**

Table 17. Cooling Water

Electricity		
Process Units	Power Output (hp)	Electricity Requirement (kW)
PE-101	64.2	47.9
PE-102	10.5	7.9
PE-103	7.8	5.8
PD-101	1.2	0.9
PD-102	56.5	42.1
PD-103	40.1	29.9
PD-104	0.2	0.1
PD-105	30.8	23.0
PD-106	41.6	31.0
PD-107	1.1	0.8
PF-101	206.1	153.7
PF-102	33.4	24.9
PF-103	1.5	1.1
PF-104	0.8	0.6
PF-105	15.2	11.3
PF-106	1.5	1.1
PF-107	21.2	15.8
PF-108	1.5	1.1
PF-109	24.8	18.5
PF-110	5.5	4.1
PF-111 to PF-118	686.6	512.0
P-F19 to P-F26	450.6	336.0
PF-127	166.3	124.0
PF-128	322.2	240.3
PR-101	0.0	0.0
PR-102	4.0	3.0
R-101	9.5	7.1
CF-101	1,901.3	1,417.8
MF-101	374.8	279.5
MF-102	591.6	441.2
Total	**5,072.3**	**3,782.5**

Table 18. Electricity

It is worth noting that a heat integration process for the proposed design was attempted, but found to be economically less favorable than simply using available steam utility. All usable hot streams within the process are not hot enough to drive any of the required unit processes for which steam is used. Attempts were made to use inter-process hot streams to pre-heat water for steam, and then heat the water using a hydrocarbon fired furnace or other direct heating unit processes. At the assumed base price of steam (taken from *Seider, Seader, Lewin and Widagdo*), these alternative heat integration processes were found to be economically unfavorable to the direct purchase of steam utility. If energy prices climb, however, it could become economically feasible to pre-heat reboiler quality water with certain process streams and use on site process units to make appropriate quality steam to drive the necessary unit processes elsewhere in the design. Further analysis and data on the local availability and prices of steam utilities for the proposed design could better inform this analysis and possibly yield NPV positive alternatives to the proposed utility sources. An analysis of the effects of steam utility costs on the NPV of the proposed design are discussed and shown in the Economic Sensitivities section of the report on page 185 and in Table 30.

Equipment List and Unit Descriptions

Total Equipment List

Equipment Cost Summary				
Unit Name	**Type**	**Purchase Cost**	**Bare Module Factor**	**Bare Module Cost**
PE-101 Pump	Process Machinery	$16,600	4.73	$78,600
PE-102 Pump	Process Machinery	$8,000	6.85	$54,800
PE-103 Pump	Process Machinery	$5,500	6.95	$38,200
PD-101 Pump	Process Machinery	$11,100	6.20	$68,800
PD-102 Reflux Pump	Process Machinery	$8,500	6.54	$55,600
PD-103 Pump	Process Machinery	$13,800	4.89	$67,500
PD-104 Pump	Process Machinery	$4,700	7.96	$37,400
PD-105 Reflux Pump	Process Machinery	$95,900	2.76	$264,700
PD-106 Pump	Process Machinery	$4,100	6.80	$27,900
PD-107 Reflux Pump	Process Machinery	$7,800	6.06	$47,300
PF-101 Pump	Process Machinery	$36,300	3.21	$116,523
PF-102 Pump	Process Machinery	$29,400	3.21	$94,374
PF-103 Pump	Process Machinery	$24,400	3.21	$78,324
PF-104 Pump	Process Machinery	$24,400	3.21	$78,324
PF-105 Pump	Process Machinery	$24,400	3.21	$78,324
PF-106 Pump	Process Machinery	$24,400	3.21	$78,324
PF-107 Pump	Process Machinery	$29,400	3.21	$94,374
PF-108 Pump	Process Machinery	$27,600	3.21	$88,596
PF-109 Pump	Process Machinery	$79,100	3.21	$253,911
PF-110 Pump	Process Machinery	$25,000	3.21	$80,250
PF-111 (to 118) 8 Pumps	Process Machinery	$235,200	3.21	$754,992
PF-119 (to 126) 8 Pumps	Process Machinery	$525,600	3.21	$1,687,176
PF-127 Pump	Process Machinery	$148,500	3.21	$476,685
PF-128 Pump	Process Machinery	$140,500	3.21	$451,005
PR-101 Pump	Process Machinery	$4,200	6.17	$25,900
PR-102 Pump	Process Machinery	$42,900	3.21	$137,709
FF-101 Seed Fermenter	Fabricated Equipment	$81,000	3.21	$260,010
FF-102 Seed Fermenter	Fabricated Equipment	$100,300	3.21	$321,963
FF-103 Seed Fermentered	Fabricated Equipment	$436,200	3.21	$1,400,202
FF-104 Production Vessel	Fabricated Equipment	$2,995,400	3.21	$9,615,234
FF-105 Production Vessel	Fabricated Equipment	$2,995,400	3.21	$9,615,234
FF-106 Production Vessel	Fabricated Equipment	$2,995,400	3.21	$9,615,234
FF-107 Production Vessel	Fabricated Equipment	$2,995,400	3.21	$9,615,234
FF-108 Production Vessel	Fabricated Equipment	$2,995,400	3.21	$9,615,234
FF-109 Production Vessel	Fabricated Equipment	$2,995,400	3.21	$9,615,234
FF-110 Production Vessel	Fabricated Equipment	$2,995,400	3.21	$9,615,234
FF-111 Production Vessel	Fabricated Equipment	$2,995,400	3.21	$9,615,234
FE-101 Flash Vessel	Fabricated Equipment	$161,600	4.42	$713,703
FE-102 Flash Vessel	Fabricated Equipment	$163,400	4.99	$816,064
FE-103 Flash Vessel	Fabricated Equipment	$149,000	5.40	$805,286
FE-104 Flash Vessel	Fabricated Equipment	$79,300	6.14	$487,178
FE-105 Flash Vessel	Fabricated Equipment	$49,200	6.06	$297,972

Equipment Cost Summary				
Unit Name	**Type**	**Purchase Cost**	**Bare Module Factor**	**Bare Module Cost**
HXF-101 Water Sterilizer	Process Machinery	$193,000	3.21	$619,530
HXF-102 Sugar Sterilizer	Process Machinery	$1,147,900	3.21	$3,684,759
HXF-103 (to 113) 11 Heat Exchangers	Process Machinery	$609,400	3.21	$1,956,174
HXF-114 Killing Unit	Process Machinery	$242,700	3.21	$779,067
HX-103 Condenser	Process Machinery	$82,900	2.46	$204,000
HX-105 Heat Exchanger	Process Machinery	$17,500	5.14	$89,900
HX-106 Heat Exchanger	Process Machinery	$26,100	4.12	$107,500
HX-107 Heat Exchanger	Process Machinery	$63,800	2.75	$175,400
HX-108 Heat Exchanger	Process Machinery	$725,600	3.21	$2,329,176
HX-109 Heat Exchanger	Process Machinery	$8,000	5.60	$44,800
HX-110 Condenser	Process Machinery	$82,900	2.46	$204,000
HX-111 Condenser	Process Machinery	$242,000	1.70	$411,900
HX-112 Condenser	Process Machinery	$21,000	4.19	$88,000
D-101 Tower	Fabricated Equipment	$1,103,800	1.74	$1,921,400
D-102 Tower	Fabricated Equipment	$2,819,700	2.00	$5,627,900
D-103 Tower	Fabricated Equipment	$87,200	3.59	$312,800
RB-101 Reboiler	Process Machinery	$1,209,800	1.26	$1,520,500
RB-102 Reboiler	Process Machinery	$179,900	1.92	$345,500
RB-103 Reboiler	Process Machinery	$56,700	2.53	$143,500
RD-101 Reflux Accumulator	Process Machinery	$22,300	5.83	$130,100
RD-102 Reflux Accumulator	Process Machinery	$65,200	4.34	$282,900
RD-103 Reflux Accumulator	Process Machinery	$20,600	6.22	$128,100
R-101 Reaction Vessel	Fabricated Equipment	$225,300	1.82	$410,600
STF-101 Seed Storage Tank	Fabricated Equipment	$290,700	3.21	$933,147
ST-102 Product Storage	Fabricated Equipment	$2,433,500	3.21	$7,811,535
AF-101 Air Filter	Process Machinery	$2,300	3.21	$7,383
CF-101 Centrifuge	Process Machinery	$280,400	3.21	$900,084
MF-101 Media Mixing Tank (2 Tanks)	Fabricated Equipment	$4,915,700	3.21	$15,779,397
MF-102 Sugar Mixing Tank	Fabricated Equipment	$6,052,300	3.21	$19,427,883
Spare Pumps	Spares	$1,597,300	3.33	$5,315,591
Total				***159,032,366***

Table 19. Equipment Cost Summary – Estimated Bare Module Costs

Of the $159 million total bare module cost, approximately $77 million comes from the bare module costs associated with the process fermenters (FF-104 to FF-111). This is due to scale of each vessel (roughly 500,000 gallons each), and the material requirements of using stainless steel for more feasible sterilization during cleaning procedures. The methods used for sizing each fermenter are summarized in Appendix IV - Design Calculations on page 234 of the design report. It is worth noting that cost estimations suggested by *Seider, Seader, Lewin and Widagdo*, suggest that a single larger vessel for fermentation would decrease the total bare module costs, however it was assumed infeasible to have fermentation vessels larger than 500,000 gallons and thus the total fermentation volume required for the process was split among 8 vessels, to get each vessel's volume less than 500,000 gallons.[14]

The large scale required for the fermentation vessels stems from the final concentration of 3-HP in the fermentation broth, assuming a 1:1.85 molar conversion of glucose to 3-HP and a 10% by mass upper limit on the glucose concentration of growth media. The specific fermentation volume calculation is shown in Appendix IV - Design Calculations on page 234. It is worth noting that changes in the maximum final concentration of 3-HP in fermentation broth would significantly affect the required fermentation volume, and correspondingly the bare module costs of fermentation vessels. Laboratory level exploration on the maximum feasible 3-HP concentration could better inform these assumptions and possibly lower estimated volume and cost requirements. An analysis of the effects of changes in batch and maximum possible 3-HP concentration in fermentation on the bare module cost of the fermenters is shown in Table 32 on page 190 of the design report.

It is also worth noting that the mixing tanks in the fermentation parts of the process have exceptionally large volume and require impellers to induce agitation and complete mixing. This requirement significantly increases the bare module costs of the process units and any decreases in the total volume (specifically the water content) of the process could significantly decrease this portion of total bare module cost.

[14] This bound was based on suggestions by Mr. Stephen M. Tieri and corroborated by Mr. Bruce Vrana.

Unit Descriptions

Costing for all equipment was based on values provided by Aspen IPE, as discussed in Appendix IV - Design Calculations, on page 235 of the design report. Additionally, Aspen result reports for a sample distillation column (D-101), a flash vessel (FE-101), a pump (PD-101) and a reactor vessel (R-101) are shown in Appendix II – Aspen Input / Report Summary from pages 213 to 224 of the report. Other process units are discussed in detail in the appropriate section, with associated Aspen results and design calculations referenced.

Pumps

Sample calculations for determining the pump head and electricity requirements are provided in Appendix IV - Design Calculations, on page 233.

PE-101 - Base Purchase Cost: $16,600

This is a centrifugal pump constructed of carbon steel that brings the fermentation product from the fermentation process to the first flash vessel of the flash evaporation process, FE-101. SE-101 flows at a rate of 703,579.3 lb/hr and a temperature of 98.6°F. The pump has a brake power of 64.2 hp, a pump head of 139.1 ft, and an electrical requirement of 47.9 kW. It raises the pressure of the stream from 14.7 psi to 75.0 psi.

PE-102 - Base Purchase Cost: $8,000

This is a centrifugal pump constructed of carbon steel that brings process water to the heat exchangers utilized in the flash evaporation process. SE-121 flows at 227,082.6 lb/hr and a temperature of 77.0°F. The pump has a brake power of 10.6 hp, a pump head of 64.8 ft, and an electrical requirement of 7.9 kW. The pressure of the stream rises from 14.7 psi to 42.6 psi.

PE-103 - Base Purchase Cost: $5,500

This is a centrifugal pump constructed of carbon steel that brings concentrated 3-HP from the final flash evaporator in the series, FE-105, to the reactor vessel, R-101. SE-119 enters the pump at a flow rate of 69,525.2 lb/hr. The pump is designed with a brake power of 7.8 hp, a pump head of 125.2 ft, and an electrical requirement of 5.8 kW. The pressure of the stream is increased from 14.7 psi to 74.0 psi.

PD-101 - Base Purchase Cost: $11,100

This is a carbon steel centrifugal pump that pumps the bottoms product from the first distillation column, D-101, to the second distillation column, D-102. SR-119 flows through the pump at 462,110.8 lb/hr. The pump operates with a brake power of 1.2 hp, a pump head of 3.8 ft and at 0.86 kW. The stream passing through this pump has a pressure change of 1.5 psi, increasing from 22.7 psi to 24.2 psi.

PD-102 - Base Purchase Cost: $8,500

This is a carbon steel centrifugal pump connected to distillation column, D-101. It used to pump the reflux to the top tray. The mass flow rate is 108,305.7 lb/hr. The pump is designed to have a brake power of 15.0 hp, a pump head of 78.5 ft and has an electricity requirement of 42.1 kW.

PD-103 - Base Purchase Cost: $13,800

This is a carbon steel centrifugal pump that pumps the recycle stream from D-102 to the reactor vessel, R-101. SD-110 flows through the pump at 410,920.4 lb/hr. The pump operates with a brake power of 40.1 hp, a pump head of 147.4 ft and an electricity requirement of 29.9 kW. The stream passing through experiences an increase in pressure from 16.2 psi to 74.0 psi.

PD-104 - Base Purchase Cost: $4,700

This is a carbon steel centrifugal pump that pumps the bottoms product from the second distillation column, D-102, to the third distillation column, D-103. SD-108 flows through the pump at 47,039.7 lb/hr. The pump operates with a brake power of 0.2 hp, a pump head of 3.8 ft and an electricity requirement of 0.1 kW. The stream passing through this pump has a pressure change of 1.4 psi, increasing from 21.3 psi to 22.7 psi.

PD-105 - Base Purchase Cost: $95,900

This is a carbon steel centrifugal pump connected to distillation column D-102. It is used to pump the reflux to the top tray. The mass flow rate is 415,060.7 lb/hr. The pump is designed to have a brake power of 30.8 hp, a pump head of 150.0 ft, and an electricity requirement of 23.0 kW.

PD-106 - Base Purchase Cost: $4,100

This is a carbon steel centrifugal pump connected to distillation column D-103. It used to pump the reflux to the top tray. The mass flow rate is 131,659.6 lb/hr. The pump is designed to have a brake power of 56.4 hp, a pump head of 26.0 ft, and an electricity requirement of 31.0 kW.

PD-107 - Base Purchase Cost: $4,100

This is a carbon steel centrifugal pump designed to bring the acid recycle stream to the reactor vessel, R-101. The mass flow rate is 3,125.5 lb/hr. The pump is designed to have a brake power of 1.1 hp, a pump head of 200.2 ft, and an electricity requirement of .8 kW. The stream experiences a pressure increase from 16.2 psi to 74.0 psi.

PF-101 - Base Purchase Cost: $36,300

This is a centrifugal pump constructed of carbon steel that pumps the media solution produced in the first mixer, MF-101, and passes it through a heat exchanger, HXF-101. This pump runs 16 hours per batch. The stream passing through this pump has a flow rate of 1,436,688 lb/hr. It has an electrical requirement of 153.7 kW.

PF-102 - Base Purchase Cost: $29,400

This carbon steel centrifugal pump is responsible for pumping media from the mixer, MF-102, into the seed fermentation units, FF-101 to FF-103. This unit operates for 1.25 hours per batch and has varying stream flows depending on which seed fermenter it is delivering material into. At maximum, the stream has a flow rate of 168,165 lb/hr. This unit is designed to have a brake power of 4.5 hp, a pump head of 65.7 ft, and an electricity requirement of 24.9 kW.

PF-103 - Base Purchase Cost: $24,400

This carbon steel centrifugal pump is responsible for pumping the fluid from the first seed fermenter, FF-101, into the second seed fermenter, FF-102. The flow of this stream is 12.7 lb/hr. The unit is designed to have a brake power of 1.5 hp and an electricity requirement of 1.1 kW. It operates 0.25 hours per batch.

PF-104 - Base Purchase Cost: $24,400

This carbon steel centrifugal pump is responsible for pumping the contents from the second seed fermenter, FF-102, to heat exchanger, HXF-103. This pump's flow rate is 6.3 lb/hr. It is designed to have a brake power of 0.8 hp, and an electricity requirement of 0.6 kW. This pump will need to operate 24 hours per batch.

PF-105 - Base Purchase Cost: $24,400

This carbon steel centrifugal pump is responsible for pumping the contents from the second seed fermenter, FF-102, into the third seed fermenter, FF-103. The flow of this stream is 845 lb/hr. The unit is designed to have a brake power of 15.2 hp and a pump head of 0.3 ft with an electricity requirement of 11.3 kW. The pump is expected to raise the pressure from 14.7 psi to 16.2 psi and operate for 0.75 hours per batch.

PF-106 - Base Purchase Cost: $24,400

This carbon steel centrifugal pump is responsible for pumping the contents from the third seed fermenter, FF-103, and to a heat exchanger, HXF-104. The stream passing through this pump has a flow rate of 1267.6 lb/hr. The pressure of the stream increases from 14.7 psi to 16.2 psi. The pump is designed to have a brake power of 9.8 hp, a pump head of 0.5 ft, and an electricity requirement of 1.1 kW. It is expected to operate for 24 hours per batch.

PF-107 - Base Purchase Cost: $29,400

This carbon steel centrifugal pump is responsible for pumping the contents from the third seed fermenter, FF-103, into the storage tank, STF-101. The stream passing through this pump has a flow rate of 169,010 lb/hr. This unit is designed to have a brake power of 12.3 hp and a pump head of 66 ft with an electricity requirement of 15.8 kW. It will operate 0.75 hr per batch.

PF-108 - Base Purchase Cost: $24,400

This carbon steel centrifugal pump is responsible for pumping the contents in the storage tank, STF-101, through a heat exchanger, HXF-105, before recycling the contents back into the storage tank. The stream passing through this pump has a flow rate of 1,267.6 lb/hr. This unit is designed to have a brake power of 1.5 hp and a pump head of 0.5 ft operating with an electricity requirement of 1.1 kW. It is expected to operate continuously.

PF-109 - Base Purchase Cost: $79,100

This is a carbon steel centrifugal pump with the purpose of pumping media into MF-102 into the fermenters. This unit has a brake power of 21.3 hp, a pump head of 48.5 ft, and an electricity requirement of 18.5 kW. The stream flowing through this pump has a flow rate of 1,576,546.8 lb/hr. The pump increases the pressure of the stream from 14.7 psi to 16.2 psi before depositing it into one of the eight fermenters, FF-104 to FF-111.

PF-110 - Base Purchase Cost: $25,000

This is a carbon steel centrifugal pump that pumps fluid from the storage tank, STF-101. This pump has a brake power of 1.5 hp, a pump head of 12.4 ft, and an electricity requirement of 4.1 kW. The stream passing through this pump has a flow rate of 31,689.4 lb/hr. This unit operates 4 hours per batch. It increases the pressure of the stream from 14.7 psi to 16.2 psi.

PF-111 to PF-118 - Base Purchase Cost: $235,200 (8 pumps)

These carbon steel centrifugal pumps are responsible for pumping the contents in the fermentation tanks, FF-104 to FF-111, through heat exchangers, HXF-106 to HXF-113, and then recycling them back into the fermentation units. These pumps operate with a brake power of 23.1 hp, a pump head of 34 ft, and an electricity requirement of 64.0 kW. The flow rate through these pumps is 31,689.4 lb/hr. The pumps are responsible for increasing the pressure of these streams from 14.7 psi to 16.2 psi.

PF-119 to PF-126 – Base Purchase Cost: $525,600 (8 pumps)

These carbon steel centrifugal pumps are responsible for pumping the solution from the fermentation units to the killing unit, HXF-14. Each of these pumps operates with a brake power of 13.2 hp, a pump head of 11.5 ft, and an electricity requirement of 42 kW. The streams have a flow rate of 1,056,312 lb/hr. These pumps increase the pressure of the streams from 14.7 psi to 16.2 psi. These pumps operate 3 hours per batch.

PF-127 - Base Purchase Cost: $148,500

This is a carbon steel centrifugal pump that pumps the stream from the heat exchanger, HXF-114, to the centrifuge, CF-101. This pump has a brake power of 14 hp, a pump head of 85ft, and an electricity requirement of 124 kW. SF-239 flows through at 2,112,625 lb/hr. The pressure of the stream increases from 14.7 psi to 16.2 psi and the pump operates at 12 hours per batch.

PF-128 - Base Purchase Cost: $140,500

This is a carbon steel centrifugal pump that pumps fluid from the centrifuge, C-F01, to the storage tank, ST-102. This pump has a brake power of 1.5 hp and a pump head of 64 ft. It requires 240.3 kW to operate as 1,880,732 lb/hr flow through the unit. The pressure of the stream increases from 14.7 psi to 16.2 psi.

PR-101 - Base Purchase Cost: $4,200

This is a carbon steel centrifugal pump that brings pure phosphoric acid (SR-102) at a high enough pressure to enter the reactor, R-101. The pump increases the pressure of the stream from 14.7 to 74.0 psi. The pump is designed with a brake power of .01 hp, a pump head of 55 ft, and an electricity requirement of .01 kW.

PR-102 - Base Purchase Cost: $3,700

This is a carbon steel centrifugal pump that pumps 10% of R-101's (SR-108) product through a heat exchanger. SR-108 enters the pump at a flow rate of 48,357 lb/hr. The pump is designed with a brake power of 4.0 hp, a pump head of 14.8 ft, and an electricity requirement of 3.0 kW.

Fermenters

Sample calculations for determining the size and batch time for the fermenters are provided in Appendix IV - Design Calculations, on page 234.

FF-101 - Base Purchase Cost: $81,000

This stainless steel airlift fermenter that grows a 1.5 mL inoculum of *E. coli*. Two streams (SF-113 and SF-123) bring air, media, and water into this tank. This unit has working volume of 0.38 gallons, a height of 1.3 ft, and a diameter of 0.6 ft. It operates as a batch process. The contents then exit the fermenter through streams SF-117 and SF-116.

FF-102 - Base Purchase Cost: $100,300

The stainless steel airlift fermenter is responsible for continuing the culture of bacteria produced in the first fermenter, FF-101, before moving it to an even larger fermentation unit, FF-103. Streams SF-114, SF-118, and SF-124 carry material into the fermenter, while SF-119 and SF-120 carry material out of the fermenter. This unit has a working volume of 76.1 gallons, a height of 7.6 ft, and a diameter of 3.8 ft. It operates as a batch process.

FF-103 - Base Purchase Cost: $436,200

The stainless steel airlift fermenter is responsible for continuing the culture of bacteria produced in the second fermenter, FF-102, before moving it to the storage tank, STF-101. SF-112, SF-121 and SF-125 carry material into the unit, while SF-122 and SF-127 carry material out of the fermenter. This unit has a working volume of 15,216 gallons, a height of 44.2 ft, and a diameter of 22.1 ft. It operates as a batch process.

FF-104 to FF-111 (8 fermenters) - Purchase Cost: $2,995,400 (for each fermenter)

These stainless steel airlift fermenters are responsible for culturing the bacteria that convert the sugars into 3-HP. Streams SF-156 to SF-163, SF-165-SF-172 and SF-147-SF-154 will bring the necessary components into the reactor. Upon completion of the fermentation the contents are drained, via streams SF-181-SF-188. The fermenters have a working volume of 380,424 gallons, a height of 129.3 ft, and a diameter of 64.7 ft.

Flash Vessels

Flash Vessel calculations were based on Aspen simulations, which used an NRTL thermodynamic model, summarized in the input summary provided in Appendix II – Aspen Input / Report Summary on page 205.

FE-101 - Base Purchase Cost: $161,600

This flash vessel is the first of five used to boil off the high amount of water in the fermentation product. Stream SE-102 from the fermentation purification process flows in the vessel at a flow rate of 728,165.5 lb/hr. This stream is 90.75% water by weight. The vessel is made of carbon steel and operates at a temperature of 308.0°F and a pressure of 73.5 psi. This flash vessel operates as a shell-tube heat exchanger. Steam at 150 psi flows in the vessel (tube side) to cause a vapor fraction of 0.3. Stream SE-103 flows out of the vessel at a flow rate of 534,988.6 lb/hr with 87.58% water by weight.

FE-102 - Base Purchase Cost: $163,400

The second flash vessel continues the flash evaporation system. SE-103 from FE-101 flows into the vessel at a flow rate of 534,988.6 lb/hr. The vessel is made of carbon steel and operates at a temperature of 294.3°F and a pressure of 58.8 psi with a vapor fraction of .4. SE-104, a vapor stream from FE-101 flows into the vessel on the tube side at 193,172.3 lb/hr. Stream SE-106, a liquid stream, flows out at 330,967.8 lb/hr and a temperature of 294.1°F to be cooled by HX-108 and is brought to FE-103. This stream is 80.3% water by weight. Stream SE-105, a vapor stream, flows out of the vessel at 204,020.8 lb/hr and a temperature of 294.1°F. Stream SE-107, a liquid stream flowing at 193,172.3 lb/hr, flows out of the tube side and goes to waste.

FE-103 - Base Purchase Cost: $149,000

The third flash vessel continues the flash evaporation system. Stream SE-108 from HX-108 flows in the vessel at a flow rate of 330,967.8 lb/hr. The vessel is made of carbon steel and operates at a temperature of 278.6°F and a pressure of 44.1 psi with a vapor fraction of .6. SE-105, a vapor stream from FE-102 flows into the vessel on the tube side at 204,020.8 lb/hr. Stream SE-111, a liquid stream, flows out at 167,128.7 lb/hr and a temperature of 278.6°F to be cooled by HX-107 and is brought to FE-104. This stream is 62% water by weight. Stream SE-109, a vapor stream, flows out of the vessel at 163,835.8 lb/hr and a temperature of 278.6°F. Stream SE-110, a liquid stream flowing at 204,020.8 lb/hr, flows out of the tube side and goes to waste.

FE-104 - Base Purchase Cost: $79,300

The flash vessel continues the flash evaporation system. Stream SE-112 from HX-107 flows in the vessel at a flow rate of 167,128.7 lb/hr. The vessel is made of carbon steel and operates at a temperature of 262.4°F and a pressure of 29.4 psi with a vapor fraction of .6. SE-109, a vapor stream from FE-103 flows into the vessel on the tube side at 163,835.8 lb/hr. Stream SE-115, a liquid stream, flows out at 167,128.7 lb/hr and a temperature of 270.1°F to be cooled by HX-106 and is brought to FE-105. This stream is 31.6% water by weight. Stream SE-113, a vapor stream, flows out of the vessel at 75,989.0 lb/hr and a temperature of 262.4°F. Stream SE-114, a liquid stream flowing at 163,835.8 lb/hr, flows out of the tube side and goes to waste.

FE-105 - Base Purchase Cost: $49,200

The fifth flash vessel is the last in the flash evaporation system. Stream SE-116 from HX-106 flows in the vessel at a flow rate of 91,139.7 lb/hr. The vessel is made of carbon steel and operates at a temperature of 248.0°F and a pressure of 14.7 psi with a vapor fraction of 0.5. SE-113, a vapor stream from FE-104 flows into the vessel on the tube side at 75,989.0 lb/hr. Stream SE-119, a liquid stream, flows out at 69,525.2 lb/hr and a temperature of 248.0°F. This stream is pumped by PE-103 to the reaction process. The flash evaporation successfully boils off most of the water, bringing a stream that is 88% 3-HP by weight to be dehydrated to the desired product. Stream SE-117, a vapor stream, flows out of the vessel at 21,614.5 lb/hr and a temperature of 248.0 °F. Stream SE-118, a liquid stream flowing at 75,989.0 lb/hr, flows out of the tube side and goes to waste.

Heat Exchangers

Sample calculations for determining the heat duty, heat transfer coefficient, heat transfer area, and utility requirements for these shell-tube heat exchangers are provided in Appendix IV - Design Calculations, on page 231.

HXF-101 - Base Purchase Cost: $193,000

This is a carbon steel media sterilization unit that uses steam to sterilize and heat the media-water mixture that passes through it. This heat exchanger has a heat duty of 255,730,464 BTU/hr. The mixture of media and water passes through the tube side of the heat exchanger, at a rate of 1,436,688 lb/hr. As it passes through, the solution will be heated by the steam from 70.0°F to 120°F while the pressure decreases from 16.2 psi to 14.7 psi. In the shell side, steam passes through at a rate of 276,166.8 lb/hr at 250°F and decreases in pressure from 64.7 psi to 63.2 psi.

HXF-102 - Base Purchase Cost: $1,147,900

This is a carbon steel sugar sterilization unit that uses steam to heat and sterilize the glucose feed stream. This particular heat exchanger has a heat duty of 6,975,457.7 BTU/hr with a heat transfer area of 54,400 sqft. Glucose passes through this heat exchanger at a rate of 139,858 lb/hr. The stream experiences an increase in temperature from 70°F to 120°F and decreases pressure from 16.2 and 14.7.

HXF-103 - Base Purchase Cost: $55,400

This carbon steel shell and tube heat exchanger removes excess heat produced within the fermenter, FF-102, to keep the temperature within the fermenter at 98°F. SF-143 flows through the tube side of the heat exchanger at flow rate of 6.3 lb/hr, producing a heat duty of 6.3 BTU/hr. The unit has an overall heat coefficient of 700 BTU/hr-sqft°F and a heat transfer area of 100 sqft. Heat is removed by using process water that circulates at 1.3 lb/hr at 90°F and 65 psi on the shell side. Temperature for the process water increases to 95°F while the pressure decreases to 63.5 psi. This unit operates as a batch process, operating for 24 hours per batch.

HXF-104 - Base Purchase Cost: $55,400

This carbon steel shell and tube heat exchanger is responsible for removing excess heat produced within fermenter FF-103 and maintaining the temperature at 98°F. The stream flowing through this heat exchanger on the tube side has flow rate of 1,267.6 lb/hr. It has a heat duty of 1,267.6 BTU/hr, an overall heat coefficient of 200 BTU/hr-sqft°F and a heat transfer area of 100 sqft. The heat exchanger decreases the temperature of the stream from 98°F to 97°F, and reduces the pressure from 16.2 psi to 14.7 psi. Water flows through the shell side at a rate of 253.5 lb/hr, and increases its temperature from 90°F to 95°F and decreases pressure from 65 psi to 63.5 psi. This unit operates as a batch process, operating at 24 hours per batch.

HXF-105 – Base Purchase Cost: $55,400

This carbon steel shell and tube heat exchanger is responsible for removing excess heat from the storage tank, STF-101, and maintaining the temperature at 98°F. The stream flowing through this heat exchanger on the tube side will have a flow rate of 1,267.6 lb/hr. It is designed with a heat duty of 1,267.6 BTU/hr, an overall heat coefficient of 200 BTU/hr-sqft°F and a heat transfer area of 100 sqft. The heat exchanger decreases the temperature of the stream from 98°F to 97°F and reduces the pressure from 16.2 psi to 14.7 psi. Water flows through the shell side at a rate of 197.1 lb/hr, and increases its temperature from 90°F to 95°F and decreases pressure from 65 to 63.5 psi. This unit operates as a batch process, operating 24 hours per batch.

HXF-106 to HXF-113 -Base Purchase Cost: $55,400 (for each fermenter, 8 total)

These carbon steel shell and tube heat exchangers are responsible for maintaining the temperature within the fermenters, FF-104 to FF-111, at 98°F by removing excess heat generated by the conversion of glucose to 3-HP. These heat exchangers expect to have a heat duty of 31,689 BTU/hr. They have an overall heat coefficient of 200 BTU/hr-sqft°F and a heat transfer area of 100 sqft. The stream flowing through the tubes will be 31,689 lb/hr. The stream enters at a temperature of 98°F and a pressure of 16.2 psi, and flows out of the heat exchanger at a temperature of 97°F and a pressure of 14.7 psi. Process water is used to capture the excess heat and flows through the shell side of the heat exchangers at a rate of 6,337 lb/hr. The temperature of the water rises from 90°F to 95°F while the pressure falls from 65 psi to 63.5 psi. These pumps operate as batch processes, operating for 24 hours per batch.

HX-103 - Base Purchase Cost: $82,900

HX-103 is a partial condenser designed as a carbon steel DHE fixed tube heat exchanger. The heat duty is 98,893,879 BTU/hr, the overall heat transfer coefficient is 200 BTU/hr-ft^2°F, and the heat transfer area is 4,271.8 ft^2. Cooling water at 90°F enters the partial condenser on the tube side to convert 129,765.4 lb/hr the vapor, stream SR-112, entering on the shell side, to a mixed state with .2 vapor fraction (SR-113). Cooling water exits at 120°F.

HX-105 - Base Purchase Cost: $17,500

This is the first fixed shell and tube carbon steel heat exchanger that uses process water to cool the streams that flow between the flash vessels. On the tube side, stream SE-117, a vapor stream from FE-105, flows into the heat exchanger at 21,614.5 lb/hr and a temperature of 248.0 °F, and SE-120 flows out at a temperature of 203.0 °F and goes to waste. The process water (SE-122) entering on the shell side flows at 227,082.6 lb/hr and is heated from 77.1 °F to 173.7°F. The heat duty is 21,144,208 BTU/hr and the heat transfer area is 1,400.7 ft^2.

HX-106 - Base Purchase Cost: $26,100

This is the second fixed shell and tube carbon steel heat exchanger that uses process water to cool the streams that flow between the flash vessels. On the tube side, stream SE-115, from FE-104, flows into the heat exchanger at 91,139.7 lb/hr and is cooled from 262.4°F to 250°F to be brought to FE-105. The process water (SE-123) entering on the shell side flows at 227,082.6 lb/hr and is warmed from 173.7°F to 259.8°F. The heat duty is 46,157,813 BTU/hr and the heat transfer area is 5,643.6 ft^2.

HX-107 - Base Purchase Cost: $62,800

This is the third fixed shell and tube carbon steel heat exchanger that uses process water to cool the streams that flow between the flash vessels. On the tube side, stream SE-111, from FE-103, flows into the heat exchanger at 167,128.7 lb/hr and is cooled from 278.6°F to 270.1°F to be brought to FE-104. The process water (SE-124) entering on the shell side flows at 227,082.6 lb/hr and becomes slightly vaporized. The heat duty is 86,796,853 BTU/hr and the heat transfer area is 12,935.4 sq ft.

HX-108 - Base Purchase Cost: $725,600

This is the final fixed shell and tube carbon steel heat exchangers in the flash evaporation process that use process water to cool the streams that flow between the flash vessels. On the tube side, stream SE-106, from FE-102, flows into the heat exchanger at 330,967.8 lb/hr and is cooled from 294.1°F to 270.1°F to be brought to FE-103. The process water (SE-125) entering on the shell side flows at 227,082.6 lb/hr and .5 vapor fraction stream SE-126 flows out and goes to waste. The heat duty is 44,548,041 BTU/hr and the heat transfer area is 7,414.3 ft^2.

HX-109 - Base Purchase Cost: $8,000

This fixed head carbon steel heat exchanger is designed to have purified product (SD-120) enter on the shell side at 43,886.4 lb/hr, a temperature of 291.7°F, and a pressure of 16.2 psi. The product is used to heat the reactor contents that flow at 227,082.6 lb/hr through the shell side. SR-109 experiences a temperature increase from 284.0°F to 290.8°F. This increase in temperature helps maintain the reactor temperature of 284.0°F. The heat duty is 111,443.2 BTU/hr, the overall heat transfer coefficient is 275.0 BTU/hr-ft^2°F, and the heat transfer area is 614.0 ft^2.

HX-111 - Base Purchase Cost: $242,000

HX-111 is a total condenser designed as a carbon steel DHE fixed tube heat exchanger. The heat duty is 428,205,936 BTU/hr, the overall heat transfer coefficient is 150 BTU/hr-ft^2°F, and the heat transfer area is 15,506.9 ft^2. Cooling water at 90°F and 14,273,531 lb/hr enters the total condenser on the tube side to convert 2,490,048.9 lb/hr of vapor, entering on the shell side (SD-102), to liquid. Cooling water exits at 120°F.

HX-112 - Base Purchase Cost: $21,000

HX-112 is a total condenser designed as a carbon steel DHE fixed tube heat exchanger. The heat duty is 22,309,423 BTU/hr, the overall heat transfer coefficient is 200 BTU/hr-ft^2°F, and the heat transfer area is 598.8ft^2. Cooling water at 90°F and 743,647.4 lb/hr enters the total condenser on the tube side to convert 131,659.6 lb/hr of vapor, entering on the shell side (SD-112), to liquid. Cooling water exits at 120°F.

HXF-114 - Base Purchase Cost: $242,700

This is a carbon steel shell and tube heat exchanger that kills any biomass produced in the fermentation process. The stream enters on the shell side at 2,112,625 lb/hr at a temperature of

98°F and 16.2 psi and flows out at 120°F and a pressure of 14.7 psi. On the tube side, water passes through at a temperature of 281°F and 64.7 psi and comes out at a pressure of 63.2 psi. The design of this heat exchanger has a heat duty of 46,477,758 BTU/hr, an overall heat coefficient of 250 BTU/hr-sqft°F, and a heat transfer area of 3,100 sqft.

Distillation Column

Sample calculations for determining the height, diameter, reflux ratio, shell thickness, and tray efficiency for the distillation columns are provided in Appendix IV - Design Calculations, on page 232.

D-101 - Purchase Cost: $2,819,700

This is a reactive distillation column where unreacted 3-HP is converted to acrylic acid, and water is removed in the distillate. SR-107 and SR-111 enter on stage 15 and 35, respectively. SR-111 contains carbon dioxide at 212.0°F and 145 psi and is used to prevent decarboxylic side reactions. The column has a reflux ratio of 5, a total of 35 stages, and uses a partial condenser. It is designed to be 63.5 ft with a diameter of 20.2 ft and has a .5 in shell thickness. The top tray has a temperature of 221.8°F and a pressure of 22.7 psi. The distillate (SR-112) flows through a partial condenser, HX-103, and into a reflux accumulator, RD-101. Here, SR-115 is purged to remove 17% of the water in SR-113. The bottom tray has a temperature of 310.6°F and a pressure of 22.7 psi. The bottoms go through a kettle reboiler, RB-101. SR-119 exits the bottom of the column at 462,110.8 lb/hr and is pumped through PD-101 and brought to D-102 for further distillation. SR-119 is 99% by weight acrylic acid.

D-102 - Base Purchase Cost: $1,103,800

This carbon steel distillation column is designed to purify acrylic acid further. SD-101 enters on stage 13. The column has a reflux ratio of 5, a total of 35 stages, and uses a total condenser. It is designed to be 63.5 ft with a diameter of 40.7 ft and .5 in shell thickness. The top tray has a temperature of 285.5°F and a pressure of 16.2 psi. The distillate (SR-112) flows through a total condenser, HX-111, and into a reflux accumulator, RD-102. The bottom tray has a temperature of 310.7°F and a pressure of 21.3 psi. The bottoms go through a reboiler, RB-102. SD-108 exits the bottom of the column at 47,039.7 lb/hr and is pumped through PD-102 and brought to D-103 for further distillation. SD-108 is 95% acrylic acid by weight. It is also in this part of the distillation section, that a stream in the distillates is split in order to create a recycle stream (SD-110) that is pumped to the reactor vessel at a flow rate of 410,920.4 lb/hr. SD-111, a stream flowing at 4,150.71 lb/hr is 99.8% acrylic acid by weight and is removed to be collected as a final product.

D-103 - Base Purchase Cost: $87,200

This carbon steel distillation column is designed for the primary function of separating out the phosphoric acid so that it can be recycled and used in the reactor, R-101. The column has a molar reflux ratio of 2, a total of 5 stages, and uses a total condenser. It is designed to be 11.0 ft with a diameter of 7.9 ft and has a .5 in shell thickness. SD-109 enters on stage 3 with a flow rate of 47,039.7 lb/hr and is 95% acrylic acid and 4.7% phosphoric acid by weight. The top tray has a temperature of 291.7°F and a pressure of 16.2 psi. The distillate (SD-112) flows through a total condenser, HX-112, and into a reflux accumulator, RD-103. The bottom tray has a temperature of 370.8°F and a pressure of 16.2 psi. The bottoms go through a kettle reboiler, RB-103. The bottoms (SD-118) is 70% phosphoric acid by weight and is split and purged to create a phosphoric acid purge stream (SD-121) and also to recycle phosphoric acid back to the reactor vessel (SD-122). SD-120, a stream flowing at 43,886.5 lb/hr that is 99.98% acrylic acid by weight, is removed to be taken as a final product.

Reboilers

Sample calculations for determining the heat duty, heat transfer coefficient, heat transfer area, and utility requirements for the reboilers are provided in Appendix IV - Design Calculations, on page 231.

RB-101 - Base Purchase Cost: $1,209,800

The kettle reboiler is used to convert the liquid bottoms (SR-117) to vapor to bring SR-118 back to D-101. Steam at 150 psi flowing at 146,213.2 lb/hr is used. The reboiler is designed to have a heat duty of 127,030,055 BTU/hr and a heat transfer area of 59,674.3 ft^2.

RB-102 - Base Purchase Cost: $179,900

The kettle reboiler is used to convert the liquid bottoms (SD-106) to vapor to bring SD-107 back to D-102. Steam at 150 psi flowing at 489,434.4 lb/hr is used. The reboiler is designed to have a heat duty of 425,220,615 BTU/hr and a heat transfer area of 216,423 ft^2. SD-106 flows in at 47,039.7 lb/hr.

RB-103 - Base Purchase Cost: $56,700

The kettle reboiler is used to convert the liquid bottoms (SD-116) to vapor to bring SD-117 back to D-103. Steam at 150 psi flowing at 25,464 lb/hr is used. The reboiler is designed to have a heat duty of 22,123,352.4 BTU/hr and a heat transfer area of 1,932.9 ft^2. SD-116 flows in at 3,153 lb/hr.

Reflux Accumulators

Discussion of the mean residence time to determine the volume of the reflux accumulators is provided in Appendix IV - Design Calculations on page 233.

RD-101 - Base Purchase Cost: $22,300

The reflux accumulator is a horizontal vessel, with a diameter of 5.5 ft, a length of 17.5 ft, and a volume of 3,100.4 gallons. This is based on a residence time of 10 minutes. SR-113 enters at a flow rate of 129,774.4 lb/hr. SR-115 is purged to remove 17% of the water in SR-113.

RD-102 - Base Purchase Cost: $65,200

The reflux accumulator is a horizontal vessel, with a diameter of 12.5 ft, a length of 39.5 ft, and a volume of 36,263 gallons. This is based on a residence time of 10 minutes. The mass flow rate is 2,490,048.9 lb/hr.

RD-103 - Base Purchase Cost: $20,600

The reflux accumulator is a horizontal vessel, with a diameter of 5.0 ft, a length of 15.0 ft, and a volume of 2,203.3 gallons. This is based on a residence time of 10 minutes. The mass flow rate is 131,659.6 lb/hr.

Reactor Vessel

Discussion of the mean residence time to determine the volume of the reactor vessel is provided in Appendix IV - Design Calculations, on page 233.

R-101 - Base Purchase Cost: $225,300

The reactor vessel is a carbon steel continuously stirred tank reactor where dehydration of 3-HP to acrylic acid begins. This reactor vessel is designed to operate at 284°F and 72.5 psi. Based on a residence time of 10 minutes, an agitator is used to mix the contents at 10.5 hp, requiring 7.1 kW. The feed stream from the flash evaporation process (SR-101) enters at a flow rate of 69.525.2 lb/hr and is 88% 3-HP by weight. SR-105 which contains 70% phosphoric acid by weight acts as the catalyst for the reaction and enters the vessel at 3,143.5 lb/hr. SR-106, a recycle stream consisting of 99.8% acrylic acid by weight flows at 410,920.4 lb/hr. SR-107 exits the reactor at a flow rate of 483,570 lb/hr and consists of 88% newly formed acrylic acid, and 8.9% unreacted 3-HP.

Storage Tank

Sample calculations for determining the volume of the storage tanks are provided in Appendix IV - Design Calculations, on page 234.

STF-101 - Base Purchase Cost: $290,700

This carbon steel storage tank holds the products from the seed fermentation units. It has a volume of 424,521 gallons, a height of 66.13 ft, and a diameter of 33.07 ft. The contents are then fed into the large fermenters FF-104 to FF-112.

STF-102 - Base Purchase Cost: $2,433,500

This is a carbon steel storage tank that will store the fermented 3-HP and water before it is pumped to FE-101. This unit has a volume of 3,329,000 gallons, a height of 131.4 ft and a diameter of 65.7 ft. The flow rate in is for 12 hours per batch. The flow rate out is continuous.

Air Filter

AF-101 - Base Purchase Cost: $2,300

The air filter is responsible for ensuring that no particulates or unwanted materials will enter into the process along with the air. This unit operates continuously with a stream of air flowing at a rate of about 26,820 lb/hr. The stream has a temperature of 70°F and the pressure decreases from 30 psi to 14.7 psi.

Centrifuge

Sample calculations for determining the utilities for the centrifuge are provided in Appendix IV - Design Calculations, on page 233.

CF-101 - Base Purchase Cost: $280,400

This is a centrifuge that removes the biomass from the fermentation product. This centrifuge is able to carry 2,112,625 lb/hr. The biomass and 10% of the water are removed from the stream. This unit operates for 12 hours per batch

Mixers

Sample calculations for determining the utility requirements are provided in Appendix IV - Design Calculations, on page 234.

MF-101 - Base Purchase Cost: $4,915,700

This is a carbon steel media mixer that mixes the media solution with sterilized water from two streams (SF-102 and SF-101). The volume capacity is 535,488 gal. This mixer is 71.5 ft in height and has a 35.7 ft diameter. It has 4 impellers and operates at 374.8 hp. There are two equivalent mixers that are staggered to operate every other batch.

MF-102 - Base Purchase Cost: $6,052,300

This is a carbon steel sugar mixer consisting of a single tank that mixes the glucose with the media mixture that comes from the first mixer, MF-101. This operates a batch process. The flow rate of the stream leaving the mixer is 1,576,546 lb/hr and at $98°F$. The mixer has a volume of 845,142.9 gallons, a height of 83.2 ft, a diameter of 41.6 ft, 4 impellers, and operates using 591.6 hp.

Spare Pumps

All pumps in the process have spares which were included in the calculation of total bare module costs. Each pump was assumed to have a single spare at equivalent purchase and bare module cost.

Unit Specification Sheets

Distillation Towers

Distillation Column					
Identification	Item:				Reactive Distillation Column
	Item No:				D-101
	No. Req'd				1
Function	Reactive Distillation and water removal				
Operation	Continuous				
Materials Handled:					
	Streams In:			**Streams Out:**	
	SR-107	SR-111	SR-116	SR-112 (Distillate)	SR-119 (Bottoms)
Quantity (lb/hr)	483,570.0	2.2	108,313.0	129,774.4	462,110.8
Temperature (°F)	284.0	212.0	221.4	221.8	310.6
Pressure (psi)	72.5	145.0	17.9	17.6	22.7
Composition (lb/hr)					
3-HP	43,248.7	-	-	-	199.1
Acrylic Acid	425,586.8	-	6,148.7	7,876.7	458,815.0
Carbon Dioxide	-	2.2	11.1	13.3	-
Phosphoric Acid	2,204.7	-	-	-	2,204.7
Water	12,529.7	-	102,153.2	121,884.4	891.9
Design Data:	Stages:				35.0
	Diameter (ft):				20.2
	Height (ft):				63.5
	Shell Thickness (in):				0.5
	Tray Type:				Sieve
	Materials of Construction:				Carbon Steel
Cost, CPB:	$	1,103,800.0			
Utilities:					
Comments:					

Distillation Column				
Identification	Item:			Distillation Column
	Item No:			D-102
	No. Req'd			1
Function	Acrylic Acid (product) purification			
Operation	Continuous			
Materials Handled:				
	Stream In:		**Streams Out:**	
	SD-101	SD-105	SD-102 (Distillate)	SD-108(Bottoms)
Quantity (lb/hr)	462,110.8	2,074,977.8	2,490,048.9	47,039.7
Temperature (°F)	310.6	285.5	285.5	310.7
Pressure (psi)	24.2	16.2	16.2	21.3
Composition (lb/hr)				
3-HP	199.1	-	-	199.1
Acrylic Acid	458,815.0	2,045,597.5	2,459,776.7	44,635.9
Carbon Dioxide	-	-	-	-
Phosphoric Acid	2,204.7	-	-	2,204.7
Water	891.9	29,380.3	30,272.2	-
Design Data:	Stages:			35.0
	Diameter (ft):			40.7
	Height (ft):			63.5
	Shell Thickness (in):			0.5
	Tray Type:			Sieve
	Materials of Construction:			Carbon Steel
Cost, CPB:	$	2,819,700.0		
Utilities:				
Comments:				

Distillation Column				
Identification	Item:			Distillation Column
	Item No:			D-103
	No. Req'd			1
Function	Phosphoric acid (catalyst) recovery			
Operation	Continuous			
Materials Handled:				
	Stream In:		**Streams Out:**	
	SD-109	SD-115	SD-112 (Distillate)	SD-118(Bottoms)
Quantity (lb/hr)	47,039.5	87,773.0	131,663.9	3,148.7
Temperature (°F)	310.6	291.7	291.7	370.8
Pressure (psi)	24.2	16.2	16.2	16.2
Composition (lb/hr)				
3-HP	198.7	0.2	-	198.9
Acrylic Acid	44,636.5	87,772.9	131,663.9	745.6
Carbon Dioxide	-	-	-	-
Phosphoric Acid	2,204.2	-	-	2,204.2
Water	-	-	-	-
Design Data:	Stages:			5.0
	Diameter (ft):			7.9
	Height (ft):			11.0
	Shell Thickness (in):			0.5
	Tray Type:			Sieve
	Materials of Construction:			Carbon Steel
Cost, CPB:	$	87,200.0		
Utilities:				
Comments:				

Heat Exchangers:

Heat Exchanger				
Identification	Item:			Media Sterilizer
	Item No:			HXF-101
	No. Req'd			1
Function	Sterilize Media			
Operation	Batch (16 hours per batch)			
Materials Handled:	**Shell Side - Steam**		**Tube Side**	
			Stream In:	Stream Out:
	Steam	Condensate	SF-104 (average)	SF-105 (average)
Quantity (lb/hr)	276,166.8	276,166.8	1,436,688.0	1,436,688.0
Temperature(°F)	250.0	250.0	70.0	98.0
Pressure (psi)	64.7	63.2	16.2	14.7
Composition (lb/hr)				
3-HP	-	-	-	-
Acrylic Acid	-	-	-	-
Biomass	-	-	-	-
Carbon Dioxide	-	-	-	-
Phosphoric Acid	-	-	-	-
Glucose	-	-	-	-
Media	-	-	22,148.0	22,148.0
Water	276,166.8	276,166.8	1,414,540.0	1,414,540.0
Design Data:	Heat Duty (BTU/hr):			255,730,464.0
	Overall Heat Coefficient (BTU/hr-sqft°F):			250.0
	Heat Transfer Area (sqft):			6,176.9
	Type:			Shell and Tube
	Material of Construction			
	Shell:			Carbon Steel
	Tube:			Carbon Steel
Cost, CPB:	$	193,000		
Utilities:		50 psi Steam		
Comments:				

Heat Exchanger				
Identification	Item:			Sugar Sterilizer
	Item No:			HXF-102
	No. Req'd			1
Function	Sterilize glucose feed			
Operation	Batch (16 hr per batch)			
Materials Handled:	**Shell Side - Steam**		**Tube Side**	
	Stream In:	Stream Out:	Stream In:	Stream Out:
	Steam	Condensate	SF-108	SF-109
Quantity (lb/hr)	7,532.9	7,532.9	139,858.8	139,858.8
Temperature(°F)	250.0	250.0	70.0	98.0
Pressure (psi)	64.7	63.2	16.2	14.7
Composition (lb/hr)				
3-HP	-	-	-	-
Acrylic Acid	-	-	-	-
Biomass	-	-	-	-
Carbon Dioxide	-	-	-	-
Phosphoric Acid	-	-	-	-
Glucose	-	-	139,858.8	139,858.8
Media	-	-	-	-
Water	7,532.9	7,532.9	-	-
Design Data:	Heat Duty (BTU/hr):			6,975,457.7
	Overall Heat Coefficient (BTU/hr-sqft°F):			250.0
	Heat Transfer Area (sqft):			54,400.0
	Type:			Shell and Tube
	Material of Construction			
	Shell:			Carbon Steel
	Tube:			Carbon Steel
Cost, CPB:	$	1,147,900		
Utilities:		50 psi Steam		
Comments:				

Heat Exchanger				
Identification	Item:			Seed Fermenter Cooler
	Item No:			HXF-103
	No. Req'd			1
Function	Maintain Fermenter at 98 ˚F			
Operation	Batch (24 hours per batch)			
Materials Handled:	**Shell Side**		**Tube Side**	
	Stream In:	Stream Out:	Stream In:	Stream Out:
	CWin	CWout	SF-143	SF-144
Quantity (lb/hr)	1.3	1.3	6.3	6.3
Temperature(°F)	90.0	95.0	98.0	97.0
Pressure (psi)	65.0	63.5		
Composition (lb/hr)				
3-HP	-	-	-	-
Acrylic Acid	-	-	-	-
Biomass	-	-	0.1	0.1
Carbon Dioxide	-	-	-	-
Phosphoric Acid	-	-	-	-
Glucose	-	-	-	-
Media	-	-	-	-
Water	1.3	1.3	6.2	6.2
Design Data:	Heat Duty (BTU/hr):			6.3
	Overall Heat Coefficient (BTU/hr-sqft°F):			150.0
	Heat Transfer Area (sqft):			100.0
	Type:			Shell and Tube
	Material of Construction			
	Shell:			Carbon Steel
	Tube:			Carbon Steel
Cost, CPB:	$	55,400		
Utilities:		Cooling Water		
Comments:				

Heat Exchanger				
Identification	Item:			Seed Fermenter Cooler
	Item No:			HXF-104 and HXF-105
	No. Req'd			2
Function	Maintain Fermenter at 98 ˚F			
Operation	Batch (24 hours per batch)			
Materials Handled:	**Shell Side**		**Tube Side**	
	Stream In:	Stream Out:	Stream In:	Stream Out:
	CWin	CWout	SF-132, SF-137	SF-134, SF-139
Quantity (lb/hr)	253.5	253.5	1,267.6	1,267.6
Temperature(°F)	90.0	95.0	98.0	97.0
Pressure (psi)	65.0	63.5	16.2	14.7
Composition (lb/hr)				
3-HP	-	-	-	-
Acrylic Acid	-	-	-	-
Biomass	-	-	25.4	25.4
Carbon Dioxide	-	-	-	-
Phosphoric Acid	-	-	-	-
Glucose	-	-	-	-
Media	-	-	-	-
Water	253.5	253.5	1,242.2	1,242.2
Design Data:	Heat Duty (BTU/hr):			1,267.6
	Overall Heat Coefficient (BTU/hr-sqft°F):			200.0
	Heat Transfer Area (sqft):			100.0
	Type:			Shell and Tube
	Material of Construction			
	Shell:			Carbon Steel
	Tube:			Carbon Steel
Cost, CPB:	$	55,400		
Utilities:		Cooling Water		
Comments:				

Heat Exchanger				
Identification	Item:			Fermenter Coolers
	Item No:			HXF-106 to HXF-113
	No. Req'd			8
Function	Maintain Fermenter at 98 ˚F			
Operation	Batch (16 hours per batch)			
Materials Handled:	**Shell Side**		**Tube Side**	
	Stream In:	Stream Out:	Stream In:	Stream Out:
	CWin	CWout	SF-207 to SF-214	SF-215 to SF-222
Quantity (lb/hr)	6,337.9	6,337.9	31,689.4	31,689.4
Temperature(°F)	90.0	95.0	98.0	97.0
Pressure (psi)	65.0	63.5	16.2	14.7
Composition (lb/hr)				
3-HP	-	-	2,609.5	2,609.5
Acrylic Acid	-	-	-	-
Biomass	-	-	633.8	633.8
Carbon Dioxide	-	-	-	-
Phosphoric Acid	-	-	-	-
Glucose	-	-	-	-
Media	-	-	-	-
Water	6,337.9	6,337.9	28,446.1	28,446.1
Design Data:	Heat Duty (BTU/hr):			31,689.4
	Overall Heat Coefficient (BTU/hr-sqft°F):			200.0
	Heat Transfer Area (sqft):			100.0
	Type:			Shell and Tube
	Material of Construction			
	Shell:			Carbon Steel
	Tube:			Carbon Steel
Cost, CPB:	$	55,400		
Utilities:		Cooling Water		
Comments:				

Heat Exchanger				
Identification	Item:			Heat Exchanger
	Item No:			HX-103
	No. Req'd			1
Function	Partially Condense Vapor from D-101			
Operation	Continuous			
Materials Handled:	**Shell Side**		**Tube Side**	
	Stream In:	Stream Out:	Stream In:	Stream Out:
	SR-112	SR-113	CWin	CWout
Quantity (lb/hr)	21,468.7	21,468.7	3,296,462.6	3,296,462.6
Temperature(°F)	221.4	221.4	90.0	120.0
Pressure (psi)	17.6	17.6	65.0	63.5
Composition (lb/hr)				
3-HP	-	-	-	-
Acrylic Acid	1,217.2	1,217.2	-	-
Biomass	-	-	-	-
Carbon Dioxide	2.2	2.2	-	-
Phosphoric Acid	-	-	-	-
Glucose	-	-	-	-
Media	-	-	-	-
Water	20,249.3	20,249.3	3,296,462.6	3,296,462.6
Design Data:	Heat Duty (BTU/hr):			98,893,879.0
	Overall Heat Coefficient (BTU/hr-sqft°F):			200.0
	Heat Transfer Area (sqft):			4,271.8
	Type:			DHE Fixed Tube
	Material of Construction			
	Shell:			Carbon Steel
	Tube:			Carbon Steel
Cost, CPB:	$	82,900		
Utilities:		Cooling Water		
Comments:				

Heat Exchanger				
Identification	Item:			Heat Exchanger
	Item No:			HX-105
	No. Req'd			1
Function	Condense Vapor from FE-105			
Operation	Continuous			
Materials Handled:	**Shell Side**		**Tube Side**	
	Stream In:	Stream Out:	Stream In:	Stream Out:
	SE-122	SE-123	SE-117	SE-120
Quantity (lb/hr)	227,082.6	227,082.6	21,614.5	21,614.5
Temperature(°F)	77.1	173.7	248.0	203.0
Pressure (psi)	42.6	36.7	14.7	14.7
Composition (lb/hr)				
3-HP	-	-	743.5	743.5
Acrylic Acid	-	-	-	-
Biomass	-	-	-	-
Carbon Dioxide	-	-	-	-
Phosphoric Acid	-	-	-	-
Glucose	-	-	-	-
Media	-	-	-	-
Water	227,082.6	227,082.6	20,871.1	20,871.1
Design Data:	Heat Duty (BTU/hr):			21,144,208.7
	Overall Heat Coefficient (BTU/hr-sqft°F):			150.0
	Heat Transfer Area (sqft):			1,440.7
	Type:			Fixed Shell U Tube
	Material of Construction			
	Shell:			Carbon Steel
	Tube:			Carbon Steel
Cost, CPB:	$	17,500		
Utilities:				
Comments:				

Heat Exchanger				
Identification	Item:			Heat Exchanger
	Item No:			HX-106
	No. Req'd			1
Function	Cool bottoms from FE-104			
Operation	Continuous			
Materials Handled:	**Shell Side**		**Tube Side**	
	Stream In:	Stream Out:	Stream In:	Stream Out:
	SE-123	SE-124	SE-115	SE-116
Quantity (lb/hr)	227,082.6	227,082.6	91,139.7	91,139.7
Temperature(°F)	173.7	259.8	262.4	250.0
Pressure (psi)	36.7	35.3	29.4	28.7
Composition (lb/hr)				
3-HP	-	-	62,330.8	62,330.8
Acrylic Acid	-	-	-	-
Biomass	-	-	-	-
Carbon Dioxide	-	-	-	-
Phosphoric Acid	-	-	-	-
Glucose	-	-	-	-
Media	-	-	-	-
Water	227,082.6	227,082.6	28,808.9	28,808.9
Design Data:	Heat Duty (BTU/hr):			46,157,812.7
	Overall Heat Coefficient (BTU/hr-sqft°F):			375.0
	Heat Transfer Area (sqft):			5,643.6
	Type:			Fixed Shell U Tube
	Material of Construction			
	Shell:			Carbon Steel
	Tube:			Carbon Steel
Cost, CPB:	$	26,100		
Utilities:				
Comments:				

Heat Exchanger				
Identification	Item:			Heat Exchanger
	Item No:			HX-107
	No. Req'd			1
Function	Cool bottoms product of FE-102 before feed to FE-103			
Operation	Continuous			
Materials Handled:	**Shell Side**		**Tube Side**	
	Stream In:	Stream Out:	Stream In:	Stream Out:
	SE-124	SE-125	SE-111	SE-112
Quantity (lb/hr)	227,082.6	227,082.6	167,128.7	167,128.7
Temperature(°F)	259.8	257.3	278.6	270.1
Pressure (psi)	35.3	33.8	44.1	42.6
Composition (lb/hr)				
3-HP	-	-	63,562.7	63,562.7
Acrylic Acid	-	-	-	-
Biomass	-	-	-	-
Carbon Dioxide	-	-	-	-
Phosphoric Acid	-	-	-	-
Glucose	-	-	-	-
Media	-	-	-	-
Water	227,082.6	227,082.6	103,566.0	103,566.0
Design Data:	Heat Duty (BTU/hr):			86,796,853.1
	Overall Heat Coefficient (BTU/hr-sqft°F):			475.0
	Heat Transfer Area (sqft):			12,087.2
	Type:			Fixed Shell U Tube
	Material of Construction			
	Shell:			Carbon Steel
	Tube:			Carbon Steel
Cost, CPB:	$	62,800		
Utilities:				
Comments:				

Heat Exchanger				
Identification	Item:			Heat Exchanger
	Item No:			HX-108
	No. Req'd			1
Function	Cool bottoms product from FE-102			
Operation	Continuous			
Materials Handled:	**Shell Side**		**Tube Side**	
	Stream In:	Stream Out:	Stream In:	Stream Out:
	SE-125	SE-126	SE-106	SE-108
Quantity (lb/hr)	227,082.6	227,082.6	330,967.8	330,967.8
Temperature(°F)	257.3	259.7	294.1	270.1
Pressure (psi)	33.8	32.3	58.8	56.0
Composition (lb/hr)				
3-HP	-	-	65,152.3	65,152.3
Acrylic Acid	-	-	-	-
Biomass	-	-	-	-
Carbon Dioxide	-	-	-	-
Phosphoric Acid	-	-	-	-
Glucose	-	-	-	-
Media	-	-	-	-
Water	227,082.6	227,082.6	265,815.5	265,815.5
Design Data:	Heat Duty (BTU/hr):			44,548,041.3
	Overall Heat Coefficient (BTU/hr-sqft°F):			275.0
	Heat Transfer Area (sqft):			7,414.3
	Type:			Fixed Shell U Tube
	Material of Construction			
	Shell:			Carbon Steel
	Tube:			Carbon Steel
Cost, CPB:	$	725,600		
Utilities:				
Comments:				

Heat Exchanger				
Identification	Item:			Heat Exchanger
	Item No:			HX-109
	No. Req'd			1
Function	Heat reaction vessel contents			
Operation	Continuous			
Materials Handled:	**Shell Side**		**Tube Side**	
	Stream In:	Stream Out:	Stream In:	Stream Out:
	SR-109	SR-110	SD-120	SD-120
Quantity (lb/hr)	227,082.6	227,082.6	43,886.4	43,886.4
Temperature(°F)	284.0	290.8	291.7	284.6
Pressure (psi)	75.0	74.0	16.1	14.7
Composition (lb/hr)				
3-HP	4,324.9	4,324.9	-	-
Acrylic Acid	42,558.7	42,558.7	43,886.4	43,886.4
Biomass	-	-	-	-
Carbon Dioxide	-	-	-	-
Phosphoric Acid	220.5	220.5	-	-
Glucose	-	-	-	-
Media	-	-	-	-
Water	1,253.0	1,253.0	-	-
Design Data:	Heat Duty (BTU/hr):			111,443.2
	Overall Heat Coefficient (BTU/hr-sqft°F):			275.0
	Heat Transfer Area (sqft):			614.0
	Type:			Fixed Shell U Tube
	Material of Construction			
	Shell:			Carbon Steel
	Tube:			Carbon Steel
Cost, CPB:	$	8,000		
Utilities:				
Comments:				

Heat Exchanger				
Identification	Item:			Heat Exchanger
	Item No:			HX-111
	No. Req'd			1
Function	Condense vapor from D-102			
Operation	Continuous			
Materials Handled:	**Shell Side**		**Tube Side**	
	Stream In:	Stream Out:	Stream In:	Stream Out:
	SD-102	SD-103	CWin	CWout
Quantity (lb/hr)	2,490,048.9	2,490,048.9	14,273,531.2	14,273,531.2
Temperature(°F)	289.5	289.5	90.0	120.0
Pressure (psi)	16.2	16.2	65.0	63.5
Composition (lb/hr)				
3-HP	-	-	-	-
Acrylic Acid	2,459,776.7	2,459,776.7	-	-
Biomass	-	-	-	-
Carbon Dioxide	-	-	-	-
Phosphoric Acid	-	-	-	-
Glucose	-	-	-	-
Media	-	-	-	-
Water	30,272.2	30,272.2	14,273,531.2	14,273,531.2
Design Data:	Heat Duty (BTU/hr):			428,205,936.0
	Overall Heat Coefficient (BTU/hr-sqft°F):			150.0
	Heat Transfer Area (sqft):			15,506.9
	Type:			DHE Fixed Tube
	Material of Construction			
	Shell:			Carbon Steel
	Tube:			Carbon Steel
Cost, CPB:	$	242,000		
Utilities:		Cooling Water		
Comments:				

Heat Exchanger				
Identification	Item:			Heat Exchanger
	Item No:			HX-112
	No. Req'd			1
Function	Condense vapor product from D-103			
Operation	Continuous			
Materials Handled:	**Shell Side**		**Tube Side**	
	Stream In:	Stream Out:	Stream In:	Stream Out:
	CWin	CWout	SD-112	SD-113
Quantity (lb/hr)	743,647.4	743,647.4	43,886.7	43,886.7
Temperature(°F)	90.0	120.0	291.7	291.7
Pressure (psi)	65.0	63.5	16.2	16.2
Composition (lb/hr)				
3-HP	-	-	0.2	0.2
Acrylic Acid	-	-	43,886.4	43,886.4
Biomass	-	-	-	-
Carbon Dioxide	-	-	-	-
Phosphoric Acid	-	-	-	-
Glucose	-	-	-	-
Media	-	-	-	-
Water	743,647.4	743,647.4	-	-
Design Data:	Heat Duty (BTU/hr):			22,309,423.0
	Overall Heat Coefficient (BTU/hr-sqft°F):			200.0
	Heat Transfer Area (sqft):			598.8
	Type:			DHE Fixed Tube
	Material of Construction			
	Shell:			Carbon Steel
	Tube:			Carbon Steel
Cost, CPB:	$	21,000		
Utilities:		Cooling Water		
Comments:				

Heat Exchanger				
Identification	Item:			Killing Unit
	Item No:			HXF-114
	No. Req'd			1
Function	Sterilize fermentation product			
Operation	Batch (24 hours per batch)			
Materials Handled:	**Shell Side**		**Tube Side**	
	Stream In:	Stream Out:	Stream In:	Stream Out:
	SF-197	SF-239	Steam	Condensate
Quantity (lb/hr)	2,112,625.4	2,112,625.4	50,192.0	50,192.0
Temperature(°F)	98.0	120.0	281.0	281.0
Pressure (psi)	16.2	14.7	64.7	63.2
Composition (lb/hr)				
3-HP	173,967.7	173,967.7	-	-
Acrylic Acid	-	-	-	-
Biomass	42,252.5	42,252.5	-	-
Carbon Dioxide	-	-	-	-
Phosphoric Acid	-	-	-	-
Glucose	-	-	-	-
Media	-	-	-	-
Water	1,896,405.2	1,896,405.2	50,192.0	50,192.0
Design Data:	Heat Duty (BTU/hr):			46,477,758.8
	Overall Heat Coefficient (BTU/hr-sqft°F):			250.0
	Heat Transfer Area (sqft):			3,100.0
	Type:			Shell and Tube
	Material of Construction			
	Shell:			Carbon Steel
	Tube:			Carbon Steel
Cost, CPB:	$	242,700		
Utilities:		50 psi Steam		
Comments:				

Pumps

Pump		
Identification	Item:	Centrifugal Pump
	Item No:	PR-101
	No. Required:	1.0
Function	To bring phosphoric acid to reactor vessel	
Operation	Continuous	
Materials Handled:		
	Streams In:	**Streams Out:**
	SR-102	SR-103
Quantity (lb/hr)	22.1	22.1
Temperature (°F)	77.0	79.3
Pressure (psi)	14.7	74.0
Composition (lb/hr)		
3-HP	-	-
Acrylic Acid	-	-
Carbon Dioxide	-	-
Phosphoric Acid	22.1	22.1
Water	-	-
Design Data:	Density of Fluid (lb/cuft):	37.9
	Brake Power (hp):	0.0
	Pump Head (ft):	55.0
	Electricity Requirements (kW):	0.0
	Material of Construction:	Carbon Steel
Cost, CPB	$ 4,200.0	
Utilities:	Electricity	
Comments:		

Pump		
Identification	Item:	Centrifugal Pump
	Item No:	PR-102
	No. Required:	1.0
Function	Pump contents of R-101 to HX-109	
Operation	Continuous	
Materials Handled:		
	Streams In:	**Streams Out:**
	SR-108	SR-109
Quantity (lb/hr)	48,357.0	48,357.0
Temperature (°F)	284.0	284.0
Pressure (psi)	75.0	75.3
Composition (lb/hr)		
3-HP	4,324.9	4,324.9
Acrylic Acid	42,558.7	42,558.7
Carbon Dioxide	0.0	0.0
Phosphoric Acid	220.5	220.5
Water	1,253.0	1,253.0
Design Data:	Density of Fluid (lb/cuft):	57.4
	Brake Power (hp):	4.0
	Pump Head (ft):	14.8
	Electricity Requirements (kW):	3.0
	Material of Construction:	Carbon Steel
Cost, CPB	$ 3,700.0	
Utilities:	Electricity	
Comments:		

Pump		
Identification	Item:	Centrifugal Pump
	Item No:	PE-101
	No. Required:	1.0
Function	To bring fermentation product to flash evaporators	
Operation	Continuous	
Materials Handled:		
	Streams In:	**Streams Out:**
	SE-101	SE-102
Quantity (lb/hr)	703,579.3	703,579.3
Temperature (°F)	98.6	98.6
Pressure (psi)	14.7	75.0
Composition (lb/hr)		
3-HP	42,756.2	42,756.2
Acrylic Acid	-	-
Carbon Dioxide	-	-
Phosphoric Acid	-	-
Water	660,823.2	660,823.2
Design Data:	Density of Fluid (lb/cuft):	62.4
	Brake Power (hp):	64.2
	Pump Head (ft):	139.1
	Electricity Requirements (kW):	47.9
	Material of Construction:	Carbon Steel
Cost, CPB	$ 16,600.0	
Utilities:	Electricity	
Comments:		

Pump		
Identification	Item:	Centrifugal Pump
	Item No:	PE-102
	No. Required:	1.0
Function	To bring process water to HX-105	
Operation	Continuous	
Materials Handled:		
	Streams In:	**Streams Out:**
	SE-121	SE-122
Quantity (lb/hr)	227,082.6	227,082.6
Temperature (°F)	77.0	77.1
Pressure (psi)	14.7	42.6
Composition (lb/hr)		
3-HP	-	-
Acrylic Acid	-	-
Carbon Dioxide	-	-
Phosphoric Acid	-	-
Water	227,082.6	227,082.6
Design Data:	Density of Fluid (lb/cuft):	62.1
	Brake Power (hp):	10.6
	Pump Head (ft):	64.8
	Electricity Requirements (kW):	7.9
	Material of Construction:	Carbon Steel
Cost, CPB	$ 8,000.0	
Utilities:	Electricity	
Comments:		

Pump		
Identification	Item:	Centrifugal Pump
	Item No:	PE-103
	No. Required:	1.0
Function	To bring concentrated 3-HP to the reactor vessel	
Operation	Continuous	
Materials Handled:		
	Streams In:	**Streams Out:**
	SE-119	SR-101
Quantity (lb/hr)	69,525.2	69,525.2
Temperature (°F)	248.0	284.4
Pressure (psi)	14.7	74.0
Composition (lb/hr)		
3-HP	61,587.3	61,587.3
Acrylic Acid	-	-
Carbon Dioxide	-	-
Phosphoric Acid	-	-
Water	7,937.9	7,937.9
Design Data:	Density of Fluid (lb/cuft):	68.2
	Brake Power (hp):	7.8
	Pump Head (ft):	125.2
	Electricity Requirements (kW):	5.8
	Material of Construction:	Carbon Steel
Cost, CPB	$ 5,500.0	
Utilities:	Electricity	
Comments:		

Pump		
Identification	Item:	Centrifugal Pump
	Item No:	PD-101
	No. Required:	1.0
Function	To bring bottoms of D-101 to feed D-102	
Operation	Continuous	
Materials Handled:		
	Streams In:	**Streams Out:**
	SR-119	SD-101
Quantity (lb/hr)	462,110.8	462,110.8
Temperature (°F)	310.6	310.6
Pressure (psi)	22.7	24.2
Composition (lb/hr)		
3-HP	199.1	199.1
Acrylic Acid	458,815.0	458,815.0
Carbon Dioxide	0.0	0.0
Phosphoric Acid	2,204.7	2,204.7
Water	891.9	891.9
Design Data:	Density of Fluid (lb/cuft):	55.4
	Brake Power (hp):	1.2
	Pump Head (ft):	3.8
	Electricity Requirements (kW):	0.9
	Material of Construction:	Carbon Steel
Cost, CPB	$ 11,100.0	
Utilities:	Electricity	
Comments:		

Pump		
Identification	Item:	Centrifugal Pump
	Item No:	PD-102
	No. Required:	1.0
Function	To bring reflux back to D-101	
Operation	Continuous	
Materials Handled:		
	Streams In:	**Streams Out:**
	SR-114	SR-116
Quantity (lb/hr)	108,305.7	108,305.7
Temperature (°F)	221.4	221.4
Pressure (psi)	17.6	17.9
Composition (lb/hr)		
3-HP	-	-
Acrylic Acid	6,659.5	6,659.5
Carbon Dioxide	11.1	11.1
Phosphoric Acid	-	-
Water	101,635.1	101,635.1
Design Data:	Density of Fluid (lb/cuft):	57.4
	Brake Power (hp):	15.0
	Pump Head (ft):	78.5
	Electricity Requirements (kW):	42.1
	Material of Construction:	Carbon Steel
Cost, CPB	$ 8,500.0	
Utilities:	Electricity	
Comments:		

Pump		
Identification	Item:	Centrifugal Pump
	Item No:	PD-103
	No. Required:	1.0
Function	To bring the recycle stream from D-102 to the reactor vessel	
Operation	Continuous	
Materials Handled:		
	Streams In:	**Streams Out:**
	SD-110	SR-106
Quantity (lb/hr)	410,920.4	410,920.4
Temperature (°F)	289.5	290.2
Pressure (psi)	16.2	74.0
Composition (lb/hr)		
3-HP	-	-
Acrylic Acid	410,037.4	410,037.4
Carbon Dioxide	-	-
Phosphoric Acid	-	-
Water	883.0	883.0
Design Data:	Density of Fluid (lb/cuft):	56.4
	Brake Power (hp):	40.1
	Pump Head (ft):	147.4
	Electricity Requirements (kW):	29.9
	Material of Construction:	Carbon Steel
Cost, CPB	$ 13,800.0	
Utilities:	Electricity	
Comments:		

Pump		
Identification	Item:	Centrifugal Pump
	Item No:	PD-104
	No. Required:	1.0
Function	To bring bottoms of D-102 to feed D-103	
Operation	Continuous	
Materials Handled:		
	Streams In:	**Streams Out:**
	SD-108	SD-109
Quantity (lb/hr)	47,039.7	47,039.7
Temperature (°F)	310.7	310.7
Pressure (psi)	21.3	22.7
Composition (lb/hr)		
3-HP	199.1	199.1
Acrylic Acid	44,635.9	44,635.9
Carbon Dioxide	-	-
Phosphoric Acid	2,204.7	2,204.7
Water	0.0	0.0
Design Data:	Density of Fluid (lb/cuft):	55.1
	Brake Power (hp):	0.2
	Pump Head (ft):	3.8
	Electricity Requirements (kW):	0.1
	Material of Construction:	Carbon Steel
Cost, CPB	$ 4,700.0	
Utilities:	Electricity	
Comments:		

Pump		
Identification	Item:	Centrifugal Pump
	Item No:	PD-105
	No. Required:	1.0
Function	To bring reflux back to D-102	
Operation	Continuous	
Materials Handled:		
	Streams In:	**Streams Out:**
	SD-104	SD-105
Quantity (lb/hr)	415,060.7	415,060.7
Temperature (°F)	289.4	291.8
Pressure (psi)	16.2	75.0
Composition (lb/hr)		
3-HP	-	-
Acrylic Acid	414,160.0	414,160.0
Carbon Dioxide	-	-
Phosphoric Acid	-	-
Water	900.7	900.7
Design Data:	Density of Fluid (lb/cuft):	56.5
	Brake Power (hp):	30.8
	Pump Head (ft):	150.0
	Electricity Requirements (kW):	23.0
	Material of Construction:	Carbon Steel
Cost, CPB	$ 95,900.0	
Utilities:	Electricity	
Comments:		

Pump		
Identification	Item:	Centrifugal Pump
	Item No:	PD-106
	No. Required:	1.0
Function	To bring reflux back to D-103	
Operation	Continuous	
Materials Handled:		
	Streams In:	**Streams Out:**
	SD-114	SD-119
Quantity (lb/hr)	43,886.7	43,886.7
Temperature (°F)	291.7	291.7
Pressure (psi)	16.2	16.3
Composition (lb/hr)		
3-HP	0.2	0.2
Acrylic Acid	43,886.4	43,886.4
Carbon Dioxide	-	-
Phosphoric Acid	-	-
Water	-	-
Design Data:	Density of Fluid (lb/cuft):	56.4
	Brake Power (hp):	41.6
	Pump Head (ft):	26.0
	Electricity Requirements (kW):	31.0
	Material of Construction:	Carbon Steel
Cost, CPB	$ 4,100.0	
Utilities:	Electricity	
Comments:		

Pump		
Identification	Item:	Centrifugal Pump
	Item No:	PD-107
	No. Required:	1.0
Function	Acid Recycle Pump	
Operation	Continuous	
Materials Handled:		
	Streams In:	**Streams Out:**
	SD-121	SD-123
Quantity (lb/hr)	3,125.5	3,121.5
Temperature (°F)	370.8	372.6
Pressure (psi)	16.2	74.0
Composition (lb/hr)		
3-HP	196.9	196.9
Acrylic Acid	741.9	741.9
Carbon Dioxide	-	-
Phosphoric Acid	2,182.6	2,182.6
Water	-	-
Design Data:	Density of Fluid (lb/cuft):	41.6
	Brake Power (hp):	1.1
	Pump Head (ft):	200.2
	Electricity Requirements (kW):	0.8
	Material of Construction:	Carbon Steel
Cost, CPB	$ 4,100.0	
Utilities:	Electricity	
Comments:		

Pump		
Identification	Item:	Centrifugal Pump
	Item No:	PF-101
	No. Req'd	1.0
Function	Pump media to heat exchanger	
Operation	16 hours per batch	
Materials Handled:	Varies (max flows are below)	
	Streams In:	**Streams Out:**
	SF-103	SF-104
Quantity (lb/hr)	1,436,688.0	1,436,688.0
Temperature(°F)	70.0	70.0
Pressure (psi)	14.7	16.2
Composition (lb/hr)		
3-HP	-	-
Acrylic Acid	-	-
Biomass	-	-
Carbon Dioxide	-	-
Glucose	-	-
Media	22,148.0	22,148.0
Phosphoric Acid	-	-
Water	1,414,540.0	1,414,540.0
Design Data:	Density of Fluid (lb/cuft):	62.3
	Brake Power (hp):	3.6
	Pump Head (ft):	21.8
	Electricity Requirements (kW):	153.7
	Material of Construction:	Carbon Steel
Cost, CPB	$ 36,300.00	
Utilities:	8,393,249.6	BTU/batch
Comments:		

Pump		
Identification	Item:	Centrifugal Pump
	Item No:	PF-102
	No. Req'd	1.0
Function	Pump media from mixers to seed fermenters	
Operation	1.25 hours per batch	
Materials Handled:	Varies (max flow rate is below)	
	Streams In:	**Streams Out:**
	SF-106	SF-112
Quantity (lb/hr)	168,165.0	168,165.0
Temperature(°F)	98.0	98.0
Pressure (psi)	14.7	16.2
Composition (lb/hr)		
3-HP	-	-
Acrylic Acid	-	-
Biomass	-	-
Carbon Dioxide	-	-
Glucose	-	-
Media	3,363.3	3,363.3
Phosphoric Acid	-	-
Water	164,801.7	164,801.7
Design Data:	Density of Fluid (lb/cuft):	62.0
	Brake Power (hp):	4.5
	Pump Head (ft):	65.7
	Electricity Requirements (kW):	24.9
	Material of Construction:	Carbon Steel
Cost, CPB	$ 29,400.0	
Utilities:		
Comments:		

Pump		
Identification	Item:	Centrifugal Pump
	Item No:	PF-103
	No. Req'd	1.0
Function	Pump fluid from Seed Fermenter 1 to 2	
Operation	.25 hours per batch	
Materials Handled:		
	Streams In:	**Streams Out:**
	SF-117	SF-118
Quantity (lb/hr)	12.7	12.7
Temperature(°F)	98.0	98.0
Pressure (psi)	14.7	16.2
Composition (lb/hr)		
3-HP	-	-
Acrylic Acid	-	-
Biomass	0.3	0.3
Carbon Dioxide	-	-
Glucose	-	-
Media	-	-
Phosphoric Acid	-	-
Water	12.4	12.4
Design Data:	Density of Fluid (lb/cuft):	62.0
	Brake Power (hp):	1.5
	Pump Head (ft):	0.0
	Electricity Requirements (kW):	1.1
	Material of Construction:	Carbon Steel
Cost, CPB	$ 24,400.0	
Utilities:	Electricity	
Comments:		

Pump		
Identification	Item:	Centrifugal Pump
	Item No:	PF-104
	No. Req'd	1.0
Function	Pump fluid from Seed Fermenter 2 to heat exchanger	
Operation	24 hours per batch	
Materials Handled:		
	Streams In:	**Streams Out:**
	SF-142	SF-143
Quantity (lb/hr)	6.3	6.3
Temperature(°F)	98.0	98.0
Pressure (psi)	14.7	16.2
Composition (lb/hr)		
3-HP	-	-
Acrylic Acid	-	-
Biomass	0.1	0.1
Carbon Dioxide	-	-
Glucose	-	-
Media	-	-
Phosphoric Acid	-	-
Water	6.2	6.2
Design Data:	Density of Fluid (lb/cuft):	62.0
	Brake Power (hp):	0.8
	Pump Head (ft):	0.0
	Electricity Requirements (kW):	0.6
	Material of Construction:	Carbon Steel
Cost, CPB	$ 24,400.0	
Utilities:	Electricity	
Comments:		

Pump		
Identification	Item:	Centrifugal Pump
	Item No:	PF-105
	No. Req'd	1.0
Function	Pump fluid from Seed Fermenter 2 to 3	
Operation	.75 hours per batch	
Materials Handled:		
	Streams In:	**Streams Out:**
	SF-120	SF-121
Quantity (lb/hr)	845.0	845.0
Temperature(°F)	98.0	98.0
Pressure (psi)	14.7	16.2
Composition (lb/hr)		
3-HP	-	-
Acrylic Acid	-	-
Biomass	16.9	16.9
Carbon Dioxide	-	-
Glucose	-	-
Media	-	-
Phosphoric Acid	-	-
Water	828.1	828.1
Design Data:	Density of Fluid (lb/cuft):	62.0
	Brake Power (hp):	15.2
	Pump Head (ft):	0.3
	Electricity Requirements (kW):	11.3
	Material of Construction:	Carbon Steel
Cost, CPB	$ 24,400.00	
Utilities:	Electricity	
Comments:		

Pump		
Identification	Item:	Centrifugal Pump
	Item No:	PF-106
	No. Req'd	1.0
Function	Pump fluid from Seed Fermenter to heat exchanger	
Operation	24 hrs per batch	
Materials Handled:		
	Streams In:	**Streams Out:**
	SF-137	SF-138
Quantity (lb/hr)	1,267.6	1,267.6
Temperature(°F)	98.0	98.0
Pressure (psi)	14.7	16.2
Composition (lb/hr)		
3-HP	-	-
Acrylic Acid	-	-
Biomass	25.4	25.4
Carbon Dioxide	-	-
Glucose	-	-
Media	-	-
Phosphoric Acid	-	-
Water	1,242.2	1,242.2
Design Data:	Density of Fluid (lb/cuft):	62.0
	Brake Power (hp):	9.8
	Pump Head (ft):	0.5
	Electricity Requirements (kW):	1.1
	Material of Construction:	Carbon Steel
Cost, CPB	$ 24,400.0	
Utilities:	Electricity	
Comments:		

Pump		
Identification	Item:	Centrifugal Pump
	Item No:	PF-107
	No. Req'd	1.0
Function	Pump fluid from Seed Fermenter 3 to Storage Tank 1	
Operation	Batch (.75 hr per batch)	
Materials Handled:		
	Streams In:	**Streams Out:**
	SF-127	SF-128
Quantity (lb/hr)	169,010.0	169,010.0
Temperature(°F)	98.0	98.0
Pressure (psi)	14.7	16.2
Composition (lb/hr)		
3-HP	-	-
Acrylic Acid	-	-
Biomass	3,380.2	3,380.2
Carbon Dioxide	-	-
Glucose	-	-
Media	-	-
Phosphoric Acid	-	-
Water	165,629.8	165,629.8
Design Data:	Density of Fluid (lb/cuft):	62.0
	Brake Power (hp):	12.3
	Pump Head (ft):	66.0
	Electricity Requirements (kW):	15.8
	Material of Construction:	Carbon Steel
Cost, CPB	$ 29,400.00	
Utilities:	Electricity	
Comments:		

Pump		
Identification	Item:	Centrifugal Pump
	Item No:	PF-108
	No. Req'd	1.0
Function	Pump fluid from storage through heat exchanger	
Operation	Continuous (31 hrs per batch)	
Materials Handled:		
	Streams In:	**Streams Out:**
	SF-132	SF-133
Quantity (lb/hr)	1,267.6	1,267.6
Temperature(°F)	98.0	98.0
Pressure (psi)	14.7	16.2
Composition (lb/hr)		
3-HP	-	-
Acrylic Acid	-	-
Biomass	25.4	25.4
Carbon Dioxide	-	-
Glucose	-	-
Media	-	-
Phosphoric Acid	-	-
Water	1,242.2	1,242.2
Design Data:	Density of Fluid (lb/cuft):	62.0
	Brake Power (hp):	1.5
	Pump Head (ft):	0.5
	Electricity Requirements (kW):	1.1
	Material of Construction:	Carbon Steel
Cost, CPB	$ 24,400.0	
Utilities:	Electricity	
Comments:		

Pump		
Identification	Item:	Centrifugal Pump
	Item No:	PF-109
	No. Req'd	1.0
Function	Pump media into fermenters	
Operation	Batch	
Materials Handled:		
	Streams In:	**Streams Out:**
	SF-110	SF-155
Quantity (lb/hr)	1,576,546.8	1,576,546.8
Temperature(°F)	98.0	98.0
Pressure (psi)	14.7	16.2
Composition (lb/hr)		
3-HP	-	-
Acrylic Acid	-	-
Biomass	-	-
Carbon Dioxide	-	-
Glucose	139,858.8	139,858.8
Media	22,148.0	22,148.0
Phosphoric Acid	-	-
Water	1,414,540.0	1,414,540.0
Design Data:	Density of Fluid (lb/cuft):	62.0
	Brake Power (hp):	21.3
	Pump Head (ft):	48.5
	Electricity Requirements (kW):	18.5
	Material of Construction:	Carbon Steel
Cost, CPB	$ 79,100.0	
Utilities:	Electricity	
Comments:		

Pump		
Identification	Item:	Centrifugal Pump
	Item No:	PF-110
	No. Req'd	1.0
Function	Pump fluid from Storage Tank into fermenters	
Operation	Batch (4 hr per batch)	
Materials Handled:		
	Streams In:	**Streams Out:**
	SF-130	SF-164
Quantity (lb/hr)	31,689.4	31,689.4
Temperature(°F)	98.0	98.0
Pressure (psi)	14.7	16.2
Composition (lb/hr)		
3-HP	-	-
Acrylic Acid	-	-
Biomass	633.8	633.8
Carbon Dioxide	-	-
Glucose	-	-
Media	-	-
Phosphoric Acid	-	-
Water	31,055.6	31,055.6
Design Data:	Density of Fluid (lb/cuft):	62.0
	Brake Power (hp):	1.5
	Pump Head (ft):	12.4
	Electricity Requirements (kW):	4.1
	Material of Construction:	Carbon Steel
Cost, CPB	$ 25,000.0	
Utilities:	Electricity	
Comments:		

Pump		
Identification	Item:	Centrifugal Pump
	Item No:	PF-111 through PF-118
	No. Req'd	8.0
Function	Pump fluid from fermenters through heat exchangers	
Operation	Batch	
Materials Handled:		
	Streams In:	**Streams Out:**
	SF-198 to SF-206	SF-207 to SF-214
Quantity (lb/hr)	31,689.4	31,689.4
Temperature(°F)	98.0	98.0
Pressure (psi)	14.7	16.2
Composition (lb/hr)		
3-HP	2,609.5	2,609.5
Acrylic Acid	-	-
Biomass	633.8	633.8
Carbon Dioxide	-	-
Glucose	-	-
Media	-	-
Phosphoric Acid	-	-
Water	28,446.1	28,446.1
Design Data:	Density of Fluid (lb/cuft):	62.0
	Brake Power (hp):	23.1
	Pump Head (ft):	34.0
	Electricity Requirements (kW):	64.0
	Material of Construction:	Carbon Steel
Cost, CPB	$ 235,200.0	
Utilities:	Electricity	

Pump		
Identification	Item:	Centrifugal Pump
	Item No:	PF-119 through PF-126
	No. Req'd	8.0
Function	Pump fluid from fermenters to killing unit	
Operation	Batch	
Materials Handled:		
	Streams In:	**Streams Out:**
	SF-181 to SF-188	SF-189 to SF-196
Quantity (lb/hr)	1,056,312.8	1,056,312.8
Temperature(°F)	98.0	98.0
Pressure (psi)	14.7	16.2
Composition (lb/hr)		
3-HP	86,983.9	86,983.9
Acrylic Acid	-	-
Biomass	21,126.3	21,126.3
Carbon Dioxide	-	-
Glucose	-	-
Media	-	-
Phosphoric Acid	-	-
Water	948,202.6	948,202.6
Design Data:	Density of Fluid (lb/cuft):	62.0
	Brake Power (hp):	13.2
	Pump Head (ft):	11.5
	Electricity Requirements (kW):	42.0
	Material of Construction:	Carbon Steel
Cost, CPB	$ 525,600.0	
Utilities:	Electricity	
Comments:		

Pump		
Identification	Item:	Centrifugal Pump
	Item No:	PF-127
	No. Req'd	1.0
Function	Pump fluid from Killing Unit to Centrifuge	
Operation	12 hours per batch	
Materials Handled:		
	Streams In:	**Streams Out:**
	SF-239	SF-240
Quantity (lb/hr)	2,112,625.4	2,112,625.4
Temperature(°F)	248.0	248.0
Pressure (psi)	14.7	16.2
Composition (lb/hr)		
3-HP	173,967.7	173,967.7
Acrylic Acid	-	-
Biomass	42,252.5	42,252.5
Carbon Dioxide	-	-
Glucose	-	-
Media	-	-
Phosphoric Acid	-	-
Water	1,896,405.2	1,896,405.2
Design Data:	Density of Fluid (lb/cuft):	59.7
	Brake Power (hp):	14.0
	Pump Head (ft):	85.0
	Electricity Requirements (kW):	124.0
	Material of Construction:	Carbon Steel
Cost, CPB	$ 148,500.0	
Utilities:	Electricity	
Comments:		

Pump		
Identification	Item:	Centrifugal Pump
	Item No:	PF-128
	No. Req'd	1.0
Function	Pump fluid from centrifuge to storage tank	
Operation	12 hours per batch	
Materials Handled:		
	Streams In:	**Streams Out:**
	SF-242	SF-243
Quantity (lb/hr)	1,880,732.4	1,880,732.4
Temperature(°F)	70.0	70.0
Pressure (psi)	14.7	16.2
Composition (lb/hr)		
3-HP	173,967.7	173,967.7
Acrylic Acid	-	-
Biomass	-	-
Carbon Dioxide	-	-
Glucose	-	-
Media	-	-
Phosphoric Acid	-	-
Water	1,706,764.7	1,706,764.7
Design Data:	Density of Fluid (lb/cuft):	62.4
	Brake Power (hp):	1.5
	Pump Head (ft):	64.0
	Electricity Requirements (kW):	240.3
	Material of Construction:	Carbon Steel
Cost, CPB	$ 140,500.0	
Utilities:	Electricity	
Comments:		

Flash Vessels

Flash Vessel			
Identification	Item:		Flash Vessel
	Item No:		FE-101
	No. Req'd		1
Function	To boil off water off fermentation product		
Operation	Continuous		
Materials Handled			
	Stream In:	**Streams Out:**	
	SE-102	SE-103	SE-104
Quantity (lb/hr)	728,165.5	534,988.6	193,172.3
Temperature (°F)	98.6	308.0	308.0
Pressure (psi)	75.0	73.5	73.5
Composition (lb/hr)			
3-HP	67,342.4	66,429.2	913.3
Acrylic Acid	-	-	-
Carbon Dioxide	-	-	-
Phosphoric Acid	-	-	-
Water	660,823.2	468,559.4	192,259.1
Design Data:	Vapor Fraction:		0.3
	Heat Duty (BTU/hr)		331,217,356.0
	Pressure (psi):		73.5
	Temperature (°F):		308.0
	Materials of Construction:		Carbon Steel
Cost, CPB:	$ 161,600.0		
Utilities:	150 psi Steam		
Comments:			

Flash Vessel					
Identification	Item:				Flash Vessel
	Item No:				FE-102
	No. Req'd				1
Function	To continue boiling water off fermentation product				
Operation	Continuous				
Materials Handled:					
	Streams In:		**Streams Out:**		
	SE-103	SE-104 (Tube)	SE-105	SE-106	SE-107 (Tube)
Quantity (lb/hr)	534,988.6	193,172.3	204,020.8	330,967.8	193,172.3
Temperature (°F)	308.0	308.0	294.1	294.1	294.3
Pressure (psi)	73.5	73.5	58.8	58.8	72.0
Composition (lb/hr)					
3-HP	66,429.2	913.3	1,276.9	65,152.3	913.3
Acrylic Acid	-	-	-	-	-
Carbon Dioxide	-	-	-	-	-
Phosphoric Acid	-	-	-	-	-
Water	468,559.4	192,259.1	202,744.0	265,815.5	192,259.1
Design Data:	Vapor Fraction:				0.4
	Heat Duty (BTU/hr)				177,980,799.0
	Pressure (psi):				58.8
	Temperature (°F):				294.3
	Materials of Construction:				Carbon Steel
Cost, CPB:	$	163,400.0			
Utilities:					
Comments:					

Flash Vessel					
Identification	Item:				Flash Vessel
	Item No:				FE-103
	No. Req'd				1
Function	To continue boiling water off fermentation product				
Operation	Continuous				
Materials Handled:					
	Streams In:		**Streams Out:**		
	SE-105 (Tube)	SE-108	SE-109	SE-110 (Tube)	SE-111
Quantity (lb/hr)	204,020.8	330,967.8	163,835.8	204,020.8	167,128.7
Temperature (°F)	294.1	270.1	278.6	278.6	278.6
Pressure (psi)	58.8	72.0	44.1	72.0	44.1
Composition (lb/hr)					
3-HP	1,276.9	65,152.3	1,589.6	1,276.9	63,562.7
Acrylic Acid	-	-	-	-	-
Carbon Dioxide	-	-	-	-	-
Phosphoric Acid	-	-	-	-	-
Water	202,744.0	265,815.5	162,246.1	202,744.0	103,566.0
Design Data:	Vapor Fraction:				0.6
	Heat Duty (BTU/hr)				145,749,888.0
	Pressure (psi):				44.1
	Temperature (°F):				278.6
	Materials of Construction:				Carbon Steel
Cost, CPB:	$	149,000.0			
Utilities:					
Comments:					

Flash Vessel					
Identification	Item:				Flash Vessel
	Item No:				FE-104
	No. Req'd				1
Function	To continue boiling water off fermentation product				
Operation	Continuous				
Materials Handled:					
	Streams In:		**Streams Out:**		
	SE-109 (Tube)	SE-112	SE-113	SE-114 (Tube)	SE-115
Quantity (lb/hr)	163,835.8	167,128.7	75,989.0	163,835.8	91,139.7
Temperature (°F)	278.6	270.1	262.4	259.8	262.4
Pressure (psi)	44.1	42.6	29.4	42.6	29.4
Composition (lb/hr)					
3-HP	1,589.6	63,562.7	1,231.9	1,589.6	62,330.8
Acrylic Acid	-	-	-	-	-
Carbon Dioxide	-	-	-	-	-
Phosphoric Acid	-	-	-	-	-
Water	162,246.1	103,566.0	74,757.1	162,246.1	28,808.9
Design Data:	Vapor Fraction:				0.6
	Heat Duty (BTU/hr)				68,073,544.7
	Pressure (psi):				29.4
	Temperature (°F):				262.4
	Materials of Construction:				Carbon Steel
Cost, CPB:	$	79,300.0			
Utilities:					
Comments:					

Flash Vessel					
Identification	Item:				Flash Vessel
	Item No:				FE-105
	No. Req'd				1
Function	To continue boiling water off fermentation product				
Operation	Continuous				
Materials Handled:					
	Streams In:		**Streams Out:**		
	SE-113 (Tube)	SE-116	SE-117	SE-118 (Tube)	SE-119
Quantity (lb/hr)	75,989.0	91,139.7	21,614.5	75,989.0	69,525.2
Temperature (°F)	262.4	250.0	248.0	248.0	248.0
Pressure (psi)	29.4	28.7	14.7	28.7	14.7
Composition (lb/hr)					
3-HP	1,231.9	62,330.8	743.5	1,231.9	61,587.3
Acrylic Acid	-	-	-	-	-
Carbon Dioxide	-	-	-	-	-
Phosphoric Acid	-	-	-	-	-
Water	74,757.1	28,808.9	20,871.1	74,757.1	7,937.9
Design Data:	Vapor Fraction:				0.5
	Heat Duty (BTU/hr)				18,701,403.4
	Pressure (psi):				14.7
	Temperature (°F):				248.0
	Materials of Construction:				Carbon Steel
Cost, CPB:	$	49,200.0			
Utilities:					
Comments:					

Reflux Accumulators

Reflux Accumulator			
Identification	Item:		Reflux Accumulator
	Item No:		RD-101
	No. Req'd		1
Function	To bring liquid from condensor back to D-101		
Operation	Continuous		
Materials Handled:			
	Stream In:	**Streams Out:**	
	SR-113	SR-114	SR-115
Quantity (lb/hr)	129,774.4	108,305.7	21,468.7
Temperature (°F)	221.4	221.4	221.4
Pressure (psi)	17.6	17.6	17.6
Composition (lb/hr)			
3-HP	-	-	-
Acrylic Acid	7,876.7	6,659.5	1,217.2
Carbon Dioxide	13.3	11.1	2.2
Phosphoric Acid	-	-	-
Water	121,884.4	101,635.1	20,249.3
Design Data:	Diameter (ft):		5.5
	Length (ft):		17.5
	Volume (gal):		3,110.4
	Material of Construction:		Carbon Steel
Cost, CPB:	$ 22,300.0		
Utilities:			
Comments:			

Reflux Accumulator		
Identification	Item:	Reflux Accumulator
	Item No:	RD-102
	No. Req'd	1
Function	To bring liquid from condensor back to D-102	
Operation	Continuous	
Materials Handled:		
	Stream In:	**Stream Out:**
	SD-103	SD-104
Quantity (lb/hr)	2,490,048.9	2,490,048.9
Temperature (°F)	289.5	289.5
Pressure (psi)	16.2	16.2
Composition (lb/hr)		
3-HP	-	-
Acrylic Acid	2,459,776.7	2,459,776.7
Carbon Dioxide	-	-
Phosphoric Acid	-	-
Water	30,272.2	30,272.2
Design Data:	Diameter (ft):	12.5
	Length (ft):	39.5
	Volume (gal):	36,263.2
	Material of Construction:	Carbon Steel
Cost, CPB:	$ 65,200.0	
Utilities:		
Comments:		

Reflux Accumulator		
Identification	Item:	Reflux Accumulator
	Item No:	RD-103
	No. Req'd	1
Function	To bring liquid from condensor back to D-103	
Operation	Continuous	
Materials Handled:		
	Stream In:	**Stream Out:**
	SD-113	SD-114
Quantity (lb/hr)	43,886.6	43,886.6
Temperature (°F)	291.7	291.7
Pressure (psi)	16.2	16.2
Composition (lb/hr)		
3-HP	0.2	0.2
Acrylic Acid	43,886.4	43,886.4
Carbon Dioxide	-	-
Phosphoric Acid	-	-
Water	-	-
Design Data:	Diameter (ft):	5.0
	Length (ft):	15.0
	Volume (gal):	2,203.3
	Material of Construction:	Carbon Steel
Cost, CPB:	$ 20,600.0	
Utilities:		
Comments:		

Reboilers

Reboiler		
Identification	Item:	Reboiler
	Item No:	RB-101
	No. Req'd	1
Function	Reboil bottoms stream to feed vapor back into D-101	
Operation	Continuous	
Materials Handled:		
	Stream In:	**Stream Out:**
	SR-117	SR-118
Quantity (lb/hr)	462,110.8	462,110.8
Temperature (°F)	310.6	310.6
Pressure (psi)	22.7	22.7
Composition (lb/hr)		
3-HP	199.1	199.1
Acrylic Acid	458,815.0	458,815.0
Carbon Dioxide	-	-
Phosphoric Acid	2,204.7	2,204.7
Water	891.9	891.9
Design Data:	Total Amount of Steam (lb/hr):	146,213.2
	Heat Duty (BTU/hr)	127,030,055.0
	Heat Transfer Area (sqft):	59,674.3
Cost, CPB:	$ 1,209,800.0	
Utilities:	150 psi Steam	
Comments:		

Reboiler		
Identification	Item:	Reboiler
	Item No:	RB-102
	No. Req'd	1
Function	Reboil bottoms stream to feed vapor back to D-102	
Operation	Continuous	
Materials Handled:		
	Stream In:	**Stream Out:**
	SD-106	SD-107
Quantity (lb/hr)	47,039.7	47,039.7
Temperature (°F)	310.7	310.7
Pressure (psi)	21.3	21.1
Composition (lb/hr)		
3-HP	199.1	199.1
Acrylic Acid	44,635.9	44,635.9
Carbon Dioxide	-	-
Phosphoric Acid	2,204.7	2,204.7
Water	-	-
Design Data:	Total Amount of Steam (lb/hr):	489,434.4
	Heat Duty (BTU/hr)	425,220,615.0
	Heat Transfer Area (sqft):	216,423.0
Cost, CPB:	$ 179,900.0	
Utilities:	150 psi Steam	
Comments:		

Reboiler		
Identification	Item:	Reboiler
	Item No:	RB-103
	No. Req'd	1
Function	Reboil bottoms to feed vapor back into D-103	
Operation	Continuous	
Materials Handled:		
	Stream In:	**Stream Out:**
	SD-116	SD-117
Quantity (lb/hr)	3,153.0	3,153.0
Temperature (°F)	370.9	370.9
Pressure (psi)	16.2	16.2
Composition (lb/hr)		
3-HP	198.9	198.9
Acrylic Acid	749.4	749.4
Carbon Dioxide	-	-
Phosphoric Acid	2,204.7	2,204.7
Water	-	-
Design Data:	Total Amount of Steam (lb/hr):	25,464.3
	Heat Duty (BTU/hr)	22,123,352.4
	Heat Transfer Area (sqft):	1,932.9
Cost, CPB:	$ 56,700.0	
Utilities:	150 psi Steam	
Comments:		

Reaction Vessel

Reactor Vessel				
Identification	Item:			Reactor Vessel
	Item No:			R-101
	No. Req'd			1
Function	Pressure Vessel where dehydration of 3-HP first occurs			
Operation	Continuously Stirred Tank Reactor			
Materials Handled:				
	Streams In:			**Stream Out:**
	SR-101	SR-105	SR-106	SR-107
Quantity (lb/hr)	69,525.2	3,143.5	410,920.4	483,570.0
Temperature (°F)	248.4	370.6	290.2	284.0
Pressure (psi)	74.0	74.0	74.0	72.5
Composition (lb/hr)				
3-HP	61,587.3	196.9	-	43,248.7
Acrylic Acid	-	741.9	410,037.4	425,586.8
Carbon Dioxide	-	-	-	-
Phosphoric Acid	-	2,204.7	-	2,204.7
Water	7,937.9	-	883.0	12,529.7
Design Data:				
	Temperature (°F):		284.0	
	Pressure (psi):		72.5	
	Material of Construction:		Carbon Steel	
	Agitator to mix contents			
	Motor Capacity (hp)		10.5	
	Electricity Requirements (kW)		7.1	
Cost, CPB:	$	225,300.0		
Utilities:		Electricity		
Comments:	Reaction: 3HP --> ACRYLIC ACID + WATER			

Seed Fermenters

Seed Fermenter				
Identification	Item:			Airlift Fermenter
	Item No:			FF-101
	No. Req'd			1
Function	Increase amount of bacteria from innoculum			
Operation	Batch			
Materials Handled:				
	Streams In:		**Streams Out:**	
	SF-113 (.25 hr)	SF-123 (24 hr)	SF-116 (24 hr)	SF-117 (.25 hr)
Quantity (lb/hr)	12.7	0.7	0.7	12.7
Temperature(°F)	98.0	70.0	70.0	98.0
Pressure (psi)	16.2	14.7	14.7	14.7
Composition (lb/hr)				
3-HP	-	-	-	-
Biomass	-	-	-	0.3
Air	-	0.7	0.7	-
Glucose	-	-	-	-
Media	0.3	-	-	-
Water	12.4	-	-	12.4
Design Data:	Volume (gal):			0.4
	Working Vol (gal):			0.38
	Height (ft):			1.3
	Diameter (ft):			0.6
	Material of Construction:			Stainless Steel
Cost, CPB:	$	81,000.0		
Utilities:				
Comments:				

Seed Fermenter					
Identification	Item:				Airlift Seed Fermenter
	Item No:				FF-102
	No. Req'd				1
Function	Culture Bacteria				
Operation	Batch				
Materials Handled:					
	Streams In:			**Streams Out:**	
	SF-114 (.25 hr)	SF-118 (.25 hr)	SF-124 (24 hr)	SF-119 (24 hr)	SF-120 (.75 hr)
Quantity (lb/hr)	2,522.4	12.7	134.1	0.7	845.0
Temperature(°F)	98.0	98.0	70.0	70.0	98.0
Pressure (psi)	16.2	16.2	14.7	14.7	14.7
Composition (lb/hr)					
3-HP	-	-	-	-	-
Biomass	-	0.3	-	-	16.9
Air	-	-	134.1	0.7	-
Glucose	-	-	-	-	-
Media	38.0	-	-	-	-
Water	2,484.4	12.4	-	-	828.1
Design Data:	Volume (gal):				84.9
	Working Vol (gal):				76.1
	Height (ft):				7.6
	Diameter (ft):				3.8
	Material of Construction:				Stainless Steel
Cost, CPB:	$		100,300.0		
Utilities:					
Comments:					

Seed Fermenter					
Identification	Item:				Airlift Seed Fermenter
	Item No:				FF-103
	No. Req'd				1
Function	Culture Bacteria				
Operation	Batch				
Materials Handled:					
	Streams In:			**Streams Out:**	
	SF-112 (.75 hr)	SF-121 (.75 hr)	SF-125 (24 hr)	SF-122 (24 hr)	SF-127 (.75 hr)
Quantity (lb/hr)	168,165.0	845.0	134.1	134.1	169,010.0
Temperature(°F)	98.0	98.0	70.0	70.0	98.0
Pressure (psi)	16.2	16.2	14.7	14.7	14.7
Composition (lb/hr)					
3-HP	-	-	-	-	-
Biomass	-	16.9	-	-	3,380.2
Air	-	-	134.1	134.1	-
Glucose	-	-	-	-	-
Media	3,363.3	-	-	-	-
Water	164,801.7	828.1	-	-	165,629.8
Design Data:	Volume (gal):				16,980.8
	Working Vol initial (gal):				15,216.0
	Height (ft):				44.2
	Diameter (ft);				22.1
	Material of Construction:				Stainless Steel
Cost, CPB:	$		436,200.0		
Utilities:					
Comments:					

Fermentation Vessels

Fermenter					
Identification	Item:				Airlift Fermenter
	Item No:				FF-104 through FF-111
	No. Req'd				8
Function	Ferment bacteria				
Operation	Batch				
Materials Handled:					
	Streams In:			**Streams Out:**	
	SF-156 to 163	SF-165 to 172	SF-147 to SF-154	SF-173 to SF-181	SF-189 to SF-196
Flow Time per batch	4 hr	1 hr	24 hr	24 hr	3 hr
Quantity (lb/hr)	788,273.4	15,844.7	4,470.0	4,470.0	1,056,312.8
Temperature(°F)	98.0	98.0	70.0	70.0	98.0
Pressure (psi)	16.2	16.2	14.7	14.7	14.7
Composition (lb/hr)					
3-HP	-	-	-	-	86,983.9
Biomass	-	316.9	-	-	21,126.3
Air	-	-	4,470.0	4,470.0	-
Glucose	69,929.4	-	-	-	-
Media	11,074.0	-	-	-	-
Water	707,270.0	15,527.8	-	-	948,202.6
Design Data:	Volume (gal):				424,521.2
	Working Vol (gal):				380,424.0
	Height (ft):				129.3
	Diameter (ft):				64.7
	Material of Construction:				Stainless Steel
Cost, CPB:	$		2,995,400.0		
Utilities:					
Comments:					

Storage Tanks

Storage Tank				
Identification	Item:			Storage Tank
	Item No:			STF-101
	No. Req'd			1
Function	Hold Seed Fermenter product until needed in large fermenters			
Operation	Batch			
Materials Handled:				
	Streams In:		**Streams Out:**	
	SF-128 (.75 hr)	SF-126 (Continuous)	SF-129 (Continuous)	SF-130
Quantity (lb/hr)	169,010.0	134.1	134.1	31,689.4
Temperature(°F)	98.0	70.0	70.0	98.0
Pressure (psi)	16.2	14.7	14.7	14.7
Composition (lb/hr)				
3-HP	-	-	-	-
Acrylic Acid	-	-	-	-
Biomass	3,380.2	-	-	633.8
Air	-	134.1	134.1	-
Carbon Dioxide	-	-	-	-
Glucose	-	-	-	-
Media	-	-	-	-
Water	165,629.8	-	-	31,055.6
Design Data:	Volume (gal)		424,521.19	
	Height (ft)		66.13	
	Diameter (ft)		33.07	
	Construction Material		Stainless Steel	
Cost, CPB:	$	290,700.0		
Utilities:				
Comments:				

Storage Tank		
Identification	Item:	Storage Tank
	Item No:	STF-102
	No. Req'd	1
Function	Stores product from batch process and feeds to continuous	
Operation	Batch	
Materials Handled:		
	Streams In:	**Streams Out:**
	SF-243 (12 hr)	SE-101 (Continuous)
Quantity (lb/hr)	1,880,732.4	703,579.3
Temperature(°F)	70.0	98.6
Pressure (psi)	16.2	14.7
Composition (lb/hr)		
3-HP	173,967.7	42,756.2
Acrylic Acid	-	-
Biomass	-	-
Carbon Dioxide	-	-
Glucose	-	-
Media	-	-
Phosphoric Acid	-	-
Water	1,706,764.7	660,823.2
Design Data:	Volume (gal):	3,329,485.7
	Height (ft):	131.4
	Diameter (ft):	65.7
	Construction Material	Carbon Steel
Cost, CPB	$ 2,433,500.0	
Utilities:		
Comments:		

Centrifuge

Centrifuge			
Identification	Item:		Centrifuge
	Item No:		CF-101
	No. Req'd		1
Function	Separate Biomass and Broth		
Operation	Batch		
Materials Handled:			
	Streams In:	**Streams Out:**	
	SF-240 (12 hr)	SF-241 (12 hr)	SF-242 (12 hr)
Quantity (lb/hr)	2,112,625.4	231,893.0	1,880,732.4
Temperature(°F)	248.0	70.0	70.0
Composition (lb/hr)			
3-HP	173,967.7	-	173,967.7
Acrylic Acid	-	-	-
Biomass	42,252.5	42,252.5	-
Air	-	-	-
Carbon Dioxide	-	-	-
Phosphoric Acid	-	-	-
Glucose	-	-	-
Media	-	-	-
Water	1,896,405.2	189,640.5	1,706,764.7
Design Data:	RPM capacity	25,000.0	
	Required Power (hp)	1,901.4	
	Required Electricity (kW)	1,417.8	
Cost, CPB:	$ 280,400.0		
Utilities:	Electricity		
Comments:			

Air Filter

Air Filter		
Identification	Item:	Air Filter
	Item No:	AFF-101
	No. Req'd	1
Function	Filter impurities out of air feed	
Operation	Continuous	
Materials Handled:	Varies (max flows are below)	
	Streams In:	**Streams Out:**
	SF-115	SF-131
Quantity (lb/hr)	27,088.2	26,954.0
Temperature(°F)	70.0	70.0
Pressure (psi)	30.0	14.7
Composition (lb/hr)		
3-HP	-	-
Acrylic Acid	-	-
Air	26,820.0	26,820.0
Biomass	-	-
Carbon Dioxide	-	-
Glucose	-	-
Media	-	-
Phosphoric Acid	-	-
Water	-	-
Design Data:	Filter Size (μm)	0.2
Cost, CPB	$ 2,300.0	
Utilities:	Electricity	
Comments:		

Mixers

Mixer			
Identification	Item:		Media Mixer
	Item No:		MF-101
	No. Req'd		2
Function	Mix media ingredients in water		
Operation	Batch		
Materials Handled:			
	Streams In:		**Streams Out:**
	SF-101 (16 hr)	SF-102 (16 hr))	SF-103
Quantity (lb/hr)	1,093,366.0	16,015.0	Varies
Temperature(°F)			
Composition (lb/hr)			
3-HP	-	-	
Acrylic Acid	-	-	
Biomass	-	-	
Air	-	-	
Carbon Dioxide	-	-	
Phosphoric Acid	-	-	
Glucose	-	-	
Media	-	16,015.0	
Water	1,093,366.0	-	
Design Data:	Volume (gal)		535,488.0
	Height (ft)		71.5
	Diameter (ft)		35.7
	Number of Impellers		4.0
	Power Needed (hp)		374.8
	Electricity Requirement (kW)		279.5
	Construction Material		Carbon Steel
Cost, CPB:	$	4,915,700.0	
Utilities:		Electricity	
Comments:			

Mixer			
Identification	Item:		Sugar Mixer
	Item No:		MF-102
	No. Req'd		1
Function	Mix glucose with water and media		
Operation	Batch		
Materials Handled:			
	Streams In:		**Streams Out:**
	SF-109 (16 hr)	SF-107 (16 hr)	SF-110 (16 hr)
Quantity (lb/hr)	122,580.0	1,103,222.0	1,225,803.0
Temperature(°F)	248.0	248.0	98.0
Composition (lb/hr)			
3-HP	-	-	-
Acrylic Acid	-	-	-
Biomass	-	-	-
Air	-	-	-
Carbon Dioxide	-	-	-
Phosphoric Acid	-	-	-
Glucose	122,580.0	-	122,580.0
Media	-	15,892.0	15,892.0
Water	-	1,087,330.0	1,087,330.0
Design Data:	Volume (gal)		845,142.9
	Height (ft)		83.2
	Diamter (ft)		41.6
	Number of Impellers		4.0
	Power Needed (hp)		591.6
	Electricity Requirement (kW)		441.2
	Construction Material		Carbon Steel
Cost, CPB:	$	6,052,300.0	
Utilities:		Electricity	
Comments:			

Capital Investment Summary

Equipment Cost Summary

Equipment Cost Summary				
Unit Name	**Type**	**Purchase Cost**	**Bare Module Factor**	**Bare Module Cost**
PE-101 Pump	Process Machinery	$16,600	4.73	$78,600
PE-102 Pump	Process Machinery	$8,000	6.85	$54,800
PE-103 Pump	Process Machinery	$5,500	6.95	$38,200
PD-101 Pump	Process Machinery	$11,100	6.20	$68,800
PD-102 Reflux Pump	Process Machinery	$8,500	6.54	$55,600
PD-103 Pump	Process Machinery	$13,800	4.89	$67,500
PD-104 Pump	Process Machinery	$4,700	7.96	$37,400
PD-105 Reflux Pump	Process Machinery	$95,900	2.76	$264,700
PD-106 Pump	Process Machinery	$4,100	6.80	$27,900
PD-107 Reflux Pump	Process Machinery	$7,800	6.06	$47,300
PF-101 Pump	Process Machinery	$36,300	3.21	$116,523
PF-102 Pump	Process Machinery	$29,400	3.21	$94,374
PF-103 Pump	Process Machinery	$24,400	3.21	$78,324
PF-104 Pump	Process Machinery	$24,400	3.21	$78,324
PF-105 Pump	Process Machinery	$24,400	3.21	$78,324
PF-106 Pump	Process Machinery	$24,400	3.21	$78,324
PF-107 Pump	Process Machinery	$29,400	3.21	$94,374
PF-108 Pump	Process Machinery	$27,600	3.21	$88,596
PF-109 Pump	Process Machinery	$79,100	3.21	$253,911
PF-110 Pump	Process Machinery	$25,000	3.21	$80,250
PF-111 (to 118) 8 Pumps	Process Machinery	$235,200	3.21	$754,992
PF-119 (to 126) 8 Pumps	Process Machinery	$525,600	3.21	$1,687,176
PF-127 Pump	Process Machinery	$148,500	3.21	$476,685
PF-128 Pump	Process Machinery	$140,500	3.21	$451,005
PR-101 Pump	Process Machinery	$4,200	6.17	$25,900
PR-102 Pump	Process Machinery	$42,900	3.21	$137,709
FF-101 Seed Fermenter	Fabricated Equipment	$81,000	3.21	$260,010
FF-102 Seed Fermenter	Fabricated Equipment	$100,300	3.21	$321,963
FF-103 Seed Fermentered	Fabricated Equipment	$436,200	3.21	$1,400,202
FF-104 Production Vessel	Fabricated Equipment	$2,995,400	3.21	$9,615,234
FF-105 Production Vessel	Fabricated Equipment	$2,995,400	3.21	$9,615,234
FF-106 Production Vessel	Fabricated Equipment	$2,995,400	3.21	$9,615,234
FF-107 Production Vessel	Fabricated Equipment	$2,995,400	3.21	$9,615,234
FF-108 Production Vessel	Fabricated Equipment	$2,995,400	3.21	$9,615,234
FF-109 Production Vessel	Fabricated Equipment	$2,995,400	3.21	$9,615,234
FF-110 Production Vessel	Fabricated Equipment	$2,995,400	3.21	$9,615,234
FF-111 Production Vessel	Fabricated Equipment	$2,995,400	3.21	$9,615,234
FE-101 Flash Vessel	Fabricated Equipment	$161,600	4.42	$713,703
FE-102 Flash Vessel	Fabricated Equipment	$163,400	4.99	$816,064
FE-103 Flash Vessel	Fabricated Equipment	$149,000	5.40	$805,286
FE-104 Flash Vessel	Fabricated Equipment	$79,300	6.14	$487,178
FE-105 Flash Vessel	Fabricated Equipment	$49,200	6.06	$297,972

Equipment Cost Summary				
Unit Name	**Type**	**Purchase Cost**	**Bare Module Factor**	**Bare Module Cost**
HXF-101 Water Sterilizer	Process Machinery	$193,000	3.21	$619,530
HXF-102 Sugar Sterilizer	Process Machinery	$1,147,900	3.21	$3,684,759
HXF-103 (to 113) 11 Heat Exchangers	Process Machinery	$609,400	3.21	$1,956,174
HXF-114 Killing Unit	Process Machinery	$242,700	3.21	$779,067
HX-103 Condenser	Process Machinery	$82,900	2.46	$204,000
HX-105 Heat Exchanger	Process Machinery	$17,500	5.14	$89,900
HX-106 Heat Exchanger	Process Machinery	$26,100	4.12	$107,500
HX-107 Heat Exchanger	Process Machinery	$63,800	2.75	$175,400
HX-108 Heat Exchanger	Process Machinery	$725,600	3.21	$2,329,176
HX-109 Heat Exchanger	Process Machinery	$8,000	5.60	$44,800
HX-110 Condenser	Process Machinery	$82,900	2.46	$204,000
HX-111 Condenser	Process Machinery	$242,000	1.70	$411,900
HX-112 Condenser	Process Machinery	$21,000	4.19	$88,000
D-101 Tower	Fabricated Equipment	$1,103,800	1.74	$1,921,400
D-102 Tower	Fabricated Equipment	$2,819,700	2.00	$5,627,900
D-103 Tower	Fabricated Equipment	$87,200	3.59	$312,800
RB-101 Reboiler	Process Machinery	$1,209,800	1.26	$1,520,500
RB-102 Reboiler	Process Machinery	$179,900	1.92	$345,500
RB-103 Reboiler	Process Machinery	$56,700	2.53	$143,500
RD-101 Reflux Accumulator	Process Machinery	$22,300	5.83	$130,100
RD-102 Reflux Accumulator	Process Machinery	$65,200	4.34	$282,900
RD-103 Reflux Accumulator	Process Machinery	$20,600	6.22	$128,100
R-101 Reaction Vessel	Fabricated Equipment	$225,300	1.82	$410,600
STF-101 Seed Storage Tank	Fabricated Equipment	$290,700	3.21	$933,147
ST-102 Product Storage	Fabricated Equipment	$2,433,500	3.21	$7,811,535
AF-101 Air Filter	Process Machinery	$2,300	3.21	$7,383
CF-101 Centrifuge	Process Machinery	$280,400	3.21	$900,084
MF-101 Media Mixing Tank (2 Tanks)	Fabricated Equipment	$4,915,700	3.21	$15,779,397
MF-102 Sugar Mixing Tank	Fabricated Equipment	$6,052,300	3.21	$19,427,883
Spare Pumps	Spares	$1,597,300	3.33	$5,315,591
Total				***159,032,366***

Table 20. Total Equipment Cost Summary

The total equipment costs, obtained from Aspen IPE, are summarized in Table 20, which contains the same information as that summarized in the total equipment list section of the report. The total bare module cost of the process equipment is estimated to be $159.0 million. The bare module costs for the fabricated equipment of vessels larger than 18 feet take into account methods suggested by Professor Leonard Fabiano for on-site fabrication of these units.

The total bare module cost of the process is then used to estimate the fixed capital requirements for the process, summarized in the subsequent section of the report.

Fixed Capital Investment

Fixed Capital Investment Summary		
Bare Module Costs		
Fabricated Equipment	$	134,248,911
Process Machinery		19,467,864
Spares		5,315,591
Storage		558,300
Other Equipment		-
Catalysts		-
Computers, Software, Etc.		-
Total Bare Module Costs:	$	159,590,666
Plus: Cost of Site Preparations		7,979,533
Plus: Cost of Service Facilities		7,979,533
Plus: Allocated Costs for utility plants and related facilities		-
Direct Permanent Investment	$	175,549,733
Plus: Cost of Contingencies & Contractor Fees		31,598,952
Total Depreciable Capital	$	207,148,684
Plus: Cost of Land		4,142,974
Plus: Cost of Royalties		-
Plus: Cost of Plant Start-Up		20,714,868
Total Unadjusted Permanent Investment	$	232,006,527
Site Factor		1.15
Total Permanent Investment	$	266,807,506

Table 21. Fixed Capital Investment Summary

Bare module costs of equipment were estimated using Aspen IPE for all available unit specifications. Once total bare module costs were estimated using this method, cost of site preparation, service facilities and allocated utility plants and related facilities were estimated according to the method described by *Seider, Seader, Lewin and Widagdo*. Specifically, the cost of site preparation was estimated as 5.0% of total bare module costs, as was cost of service facilities. Allocated costs for utility plants and related facilities were assumed to be zero for the proposed process. Cost of contingencies and contractor fees is estimated as 18.0% of direct permanent investment. Cost of land is then estimated as 2.0% of total depreciable capital, and plant start-up is then an additional 10.0% of total depreciable capital. Finally, the site factor for the proposed location of the plant is applied to the unadjusted permanent investment to get total permanent investment. The total capital investment includes total permanent investment and the net present value of working capital contributions. The specifics of working capital contributions and the net present value calculations are discussed further in the economics section of the report. The summary of total capital investment is shown in Table 22. The total capital investment is calculated assuming a CE index of 652.43 based on a logarithmic regression to extrapolate the CE index to its 2013 value. Aspen IPE costs are reported at current costs and thus were adjusted by a factor of 1.018 to adjust for the general inflation in chemical engineering process equipment.[15]

Total Capital Investment Summary		
Total Permanent Investment	$	266,807,506
Plus: Present Value of 2014 Working Capital		11,064,311
Plus: Present Value of 2015 Working Capital		4,810,570
Plus: Present Value of 2016 Working Capital		4,183,104
Total Capital Investment	**$**	**286,865,490**

Table 22. Total Capital Investment Summary

[15] [9] Chemical engineering plant cost index (cepci)

Working Capital Summary		
2014		
Accounts Receivable	$	18,936,986
Cash Reserves		2,915,307
Accounts Payable		(12,342,114)
Acrylic Acid Inventory		2,524,932
Raw Materials		688,846
Total	$	12,723,957
Discount Factor (at 15%)		0.8696
Present Value	**$**	**11,064,311**
2015		
Accounts Receivable	$	9,468,493
Cash Reserves		1,457,654
Accounts Payable		(6,171,057)
Acrylic Acid Inventory		1,262,466
Raw Materials		344,423
Total	$	6,361,979
Discount Factor (at 15%)		0.7561
Present Value	**$**	**4,810,570**
2016		
Accounts Receivable	$	9,468,493
Cash Reserves		1,457,654
Accounts Payable		(6,171,057)
Acrylic Acid Inventory		1,262,466
Raw Materials		344,423
Total	$	6,361,979
Discount Factor (at 15%)		0.6575
Present Value	**$**	**4,183,104**
Total Present Value of Working Capital	**$**	**20,057,985**

Table 23. Working Capital Summary

As seen in Table 23, working capital forms a significant part of estimated total capital investment for the proposed design. The estimates for working capital account values are based on suggestions by *Seider, Seader, Lewin and Widagdo* and are detailed in the Economic Analysis section of the report on page 182.

Other Important Considerations

Environmental Considerations

The main impact on the environment throughout this process is the waste water. We have included waste water treatment in our costs to account for this. The part of the process that contributes to the high amount of water that needs to be treated is the flash evaporation system. The water must be treated to remove any possible pollutants in the streams. This treatment will be done at on off-site facility.

This process can be considered to be carbon neutral because little carbon dioxide is produced throughout the whole process, and carbon dioxide is used to prevent decarboxylation side reactions in the distillation columns. Small amounts of carbon dioxide are produced by the fermentation process; however the amounts are only in trace concentrations and can be used and sequestered to drive the carbon dioxide requirements elsewhere in the process. Because carbon dioxide is produced in such small concentrations by the fermentation, no material environmental impact is expected to come about from the fermentation. A small scale plant would be able to verify this, and if the level of carbon dioxide output is significantly above what is expected, a carbon sequestration process may need to be integrated into the proposed design, so that environmental impact can be minimized.

Safety and Health Concerns

In order to have clean and sterilized fermentation tanks, a clean-in-place (CIP) and steam-in-place (SIP) system will be installed. As mentioned earlier this has been considered in the SuperPro scheduling for each fermenter with a CIP process time of two hours and a SIP process time of one hour. The required infrastructure in the vessels is accounted for in the cost of the fermenters. The SIP system will allow for 3,271 kg/hr steam to enter the fermenter.[16]The CIP system will use chemical solutions, CIP-100 and CIP-200, that will spray through spray nozzles, as provided by companies, such as, Steris. The SIP system will allow for steam to flow into the fermenter at 248^{o}F. The large fermenter size and the high temperature that the fermenter needs to be maintained at for roughly ½ hour to attain sterilization were taken into consideration to allot one hour for SIP.

Although the *E. coli* cells used in this process are genetically modified organisms, they pose no harm to humans. In order to deactivate the organisms before disposal, the biomass stream is heated in HXF-114. In addition, any small spills can be sent to an off-line unit for sterilization with caustic solution.

The organic acids are all flammable and some of the components used and produced are corrosive to the skin. Basic safety equipment such as lab coats, eye protective gear, and hard hats will be worn at all times in accordance to safety standards. The MSDS sheets of all the components in our process are included in Appendix V - Material Safety Data Sheets, on page 240.

Process Controllability

Throughout the process it is essential to have the equipment operating at the correct temperatures and pressures. For instance, to maintain the reactor vessel at 284^{o}F, purified acrylic acid is used to heat the reactor contents. Of high concern is the temperature and pressure control of the large-scale fermentation process. Due to the high total permanent investment cost, it is assumed that the installment and operating costs of the process control system is functionally negligible,

[16] [55] Millipore Corporation

relative to the other fixed costs of the process. In order to keep the fermenters at constant temperatures and pressures, valves and a pressure monitoring system will be in operation. Level controllers will be installed in the seed fermenters in order to eliminate the chance of overflowing or empty tanks. By ensuring steady-state and safe processes with installations of these controlling units, the proposed SuperPro schedule will be easily followed.

Plant Start-Up

At the beginning of the process year, every fermenter is to undergo a SIP process time of five days and CIP time of one day considering the large size of our fermenters. This will ensure sterility of the process and prevent buildup of contaminating biomass.

Spare equipment must be purchased in the chance that anything breaks and causes disruptions in the continuous and batch processes of the design. One spare pump for each pump in the process was added in our economic analysis and is available in the event of equipment failure. All other fixed equipment is accounted for with estimated maintenance costs in the economic analysis.

Upon plant start-up, it takes 4.5 days before the large fermenters begin producing 3-HP, as seen in the SuperPro scheduling diagram shown in the Process Description section. This startup time means that upstream disruptions take a long time for downstream effects to materialize, and with proper inter-process control and measurement, the process can easily be controlled within acceptable operating limits.

For the flash evaporation process, since the products of one flash vessel provide the heat required to operate the next flash vessel, steam at 150 psi will flow through the flash vessels at the initial start-up. Steam will flow through the first flash vessel unit, until the flash vessel reaches its unit specification. The vapor product from this vessel will then flow through to the next unit until it reaches its unit specifications. The vapor products from the flash vessels will continue to flow through to the next vessel in series until all the flash vessels reach their specified temperatures. Once these temperatures are reached, the fermentation product will be able to flow through the process to boil off the water.

Operating Cost and Economic Analysis

Operating Costs

Operating costs for the proposed plant can be broken down in two major components: Variable and Fixed Costs. Variable costs are incurred in proportion with the total operating capacity of the plant, while fixed costs are those which are relatively insensitive to change in total plant output. These costs are summarized in Table 24 and Table 25. The specific line items on each table and associated assumptions are discussed below.

Variable Cost Summary		
General Expenses		
Selling / Transfer Expenses:	$	15,360,000
Direct Research:		24,576,000
Allocated Research:		2,560,000
Administrative Expense:		10,240,000
Management Incentive Compensation:		6,400,000
Total General Expenses	$	59,136,000
Raw Materials		
Media	$	197,632,591
CO2		11,318
Phosphoric Acid		410,275
Process Water		3,591,101
Corn		77,720,027
Total Raw Materials	$	279,365,312
Utilities		
High Pressure Steam	$	37,068,996
Low Pressure Steam		7,448,007
Cooling Water		972,977
Electricity		1,691,012
Waste Water Treatment		7,781,755
Total Utilities	$	54,962,747
Total Variable Cost	**$**	**393,464,059**

Table 24. Variable Cost Summary

Fixed Cost Summary		
Operations		
Direct Wages and Benefits	$	1,092,000
Direct Salaries and Benefits		163,800
Operating Supplies and Services		65,520
Technical Assistance to Manufacturing		-
Control Laboratory		-
Total Operation	$	1,321,320
Maintenance		
Wages and Benefits	$	7,250,204
Salaries and Benefits		1,812,551
Materials and Services		7,250,204
Maintenance Overhead		362,510
Total Maintenance	$	16,675,469
Operating Overhead		
General Plant Overhead:	$	732,617
Mechanical Department Services:		247,645
Employee Relations Department:		608,795
Business Services:		763,573
Total Operating Overhead	$	2,352,631
Property Taxes and Insurance	$	4,142,974
Total Other Annual Expenses	$	-
Total Fixed Cost	**$**	**24,492,393**

Table 25. Fixed Cost Summary

General Expenses – General expenses cover expenses associated with the direct management of product within the plant, but not related to the direct manufacturing cost. This includes Selling / Transfer Expense, Direct Research, Allocated Research, Administrative Expense and Management Incentive Compensation. All General expenses are assumed as a fixed percentage of total sales, as suggested by *Seider, Seader, Lewin and Widagdo.*[17] Selling / Transfer Expenses are conservatively assumed to be 3.0% of sales; Direct Research is assumed to be 4.8% of sales; Allocated Research is assumed to be .5% of sales; Administrative Expense is assumed to be 2.0% of sales and Management Incentive Compensation is assumed to be 1.25% of sales.

[17] Table 23.1 – pg 604, Product and Process Design Principles, 3rd Edition

Raw Materials – Raw material costs are with associated the direct purchase of the feedstocks used in production. The proposed process requires 5 basic raw materials. The nutrient rich media is used as a nutrient source for the *E. coli* fermentation and is standard for *E. coli* growth medium. The media is relatively expensive and due to its completely non-renewable nature, must be consistently replenished in relatively large amounts to the fermentation sections of the process. This, along with the relatively high unit cost of the media ($4.57/kg)[18], even at industrial scale results in the highest raw material cost for the process. Carbon dioxide is applied in small amounts to the process to maintain the reactive distillation column (D-101) with a carbon dioxide rich atmosphere, used to prevent decarboxylation side reactions. Due to carbon dioxide's low solubility in aqueous solution, the amount of carbon dioxide required is relatively low and with a price of $1.52/kg – available in 10,000 kg pressurized tanks – the overall raw material cost is low.[19] Corn is the major carbohydrate source for the process and is processed to provide the glucose necessary for high levels of *E. coli* growth and 3-HP formation in the fermentation sections of the process. Since the process is assumed to be located directly next to a corn-dry grind process plant, the required infrastructure for large scale corn delivery is assumed to be present on site. The market rate for corn delivery was assumed for the process, as suggested in the problem statement and for US Midwest delivery was found to be $2.80/kg corn.[20] Phosphoric acid is used in the process as the acid catalyst for the dehydration for 3-HP to acrylic acid. Because of its high molecular weight, it is possible to efficiently separate and recycle the acid in the process resulting in a relatively high composition in the reaction steps of the process, with minimal fresh feed. Glacial phosphoric acid is assumed to be available on industrial scale at $5.51/kg, based on quoted laboratory scale prices, and using methods suggested by Mr. Bruce

[18] Media price calculation suggested by Mr. Bruce Vrana
[19] [52]Haas Group International
[20] [32] Maize (corn) daily price

Vrana to scale the quoted price to industrial scale.[21] Also required for the process is a large amount of process water which is sterilized for use in production of the media and *E. coli* growth. Process water requirements are summarized in the unit specification and process description sections of the report. The price of the process water is based on suggestions given in *Seider, Seader, Lewin and Widagdo* at $.75/1000 gal.[22]

Utilities – Utilities expenses are associated with required sources of energy, cooling capacity and heating capacity. Due to the proposed process' fermentation stage which produces relatively dilute 3-HP in aqueous solution, the separation processes used require the removal of significant amounts of water, mostly by multi-effect evaporation and distillation. These processes, though efficient in removal of water, require high levels of steam to run. Thus, the proposed process' highest utility cost is high pressure (150 psig) steam, used to drive the distillation and evaporation sections of the process. The amount of steam required is summarized in the utility requirement section of the report and the assumed price for the process comes from *Seider, Seader, Lewin and Widagdo* and is taken as $10.50/1000 kg. Due to the proximity to the industrial ethanol production plant, it is assumed that high capacity delivery of required industrial quality steam is available locally at the price cited above with appropriate infrastructure for delivery already existing. Low pressure (50 psig) is also required for the process, though only for use in sterilization within the fermentation sections of the process. The availability and price for low pressure steam is assumed to match the high pressure steam discussed above, and comes from the same source ($6.60/1000 kg). Also required for the proposed separation processes is cooling water to prevent the large scale handling of contaminated (with organic compounds) steam and vapor. Cooling water is used to condense the

[21] Phosphoric acid price calculated with assistance by Mr. Bruce Vrana
[22] Table 23.1 – pg 604, Product and Process Design Principles, 3rd Edition

vapor product of all distillation columns and in various other cooling process units (specifically to keep the production fermentation units at appropriate operating temperatures during operation). Electricity is required for use in driving agitation units as well as pumps, which provide required pressure gradients to keep flow of product through the process. The electricity requirements of the various process units which use electricity are summarized in the Utility Requirements section of the report. Again due to the plant's proximity to other industrial operations, electricity and the required infrastructure for efficient delivery is assumed to exist near the plant site. The price of electricity is assumed in accordance with *Seider, Seader, Lewin and Widagdo,* who suggest $.06/kWhr. The last required utility (Waste Water Treatment) is of significant importance to the project due to the important environmental concerns driving the project. Project specifications require minimal environmental impact from the proposed plant. Because of the large amount of separation required, a tradeoff is inevitably made between the energy requirements of the separation (and consequently steam utility costs) and the overall quality of the separation (and required waste water treatment for removal of organic contaminants from water). The proposed process leans towards higher waste water treatment costs rather than increased steam costs, based on an optimized sensitivity analysis using the effect of waste water treatment, steam and increased total investment associated with distillation columns on the NPV of the overall process. It is possible that more efficient distillation or separation methods (such as using mass separating agents) could be found which effectively eliminate the waste water treatment cost, while not significantly increasing steam utility costs. This possibility was not explored in explicit detail for this report, but a more detailed analysis may well find an NPV positive alternative in regard to the proposed separation processes and waste water treatment costs.

Fixed Cost - Operations – Fixed costs for the process were estimated according to the methods given in *Seider, Seader, Lewin and Widagdo*. Operations expense relates broadly to the cost of employees and other operators within the plant. Operations expense was thus estimated by assuming 3 operators per shift (with 5 total shifts), assuming a $35/hr direct wage per operator per shift and including 15% of the resulting yearly cost as direct salaries and benefits. Operating supplies and service was estimated as an additional 6% of direct wages and benefits. Maintenance expense was estimated, as suggested by *Seider, Seader, Lewin and Widagdo*, as wages and benefits at 3.5% of Total Depreciable Capital plus 25% of wages and benefits for salaries and benefits, plus an additional 100% of wages and benefits for materials and services plus a final 5% for maintenance overhead. Operating overhead line items were calculated as percentages of maintenance and operations wages and benefits according to *Seider, Seader, Lewin and Widagdo*. General plant overhead was estimated as 7.1% of total wages and benefits, mechanical department services was estimated as 2.4% of total wages and benefits, employee relations department was estimated as 5.9% of total wages and benefits and business services was estimated as 7.4% of total wages and benefits. Property taxes and insurance was estimated separately as 2% of total depreciable capital. Depreciation expense, though shown in the cash flow summary (Table 26), was not calculated as an operating expense and simply used the 5 MACRS depreciation schedule on total depreciable capital. The fixed cost estimates of the proposed process are summarized in Table 25.

Economic Analysis

The economic analysis of the proposed process was conducted by estimating cash flow in each period of plant operation. The method of cash flow estimation is well known to those familiar with accounting and finance principles and the full explanation and method is explained in the Appendix. Once the free cash flow in each period has been estimated, the Net Present Value (NPV) of the proposed process can be estimated by applying a discount factor (based on the assumed discount rate) to each period's cash flow and summing the overall cash flows. For the proposed process, a 15% discount rate was assumed in calculating the NPV. The discount rate in a valuation methodology should in theory reflect the perceived riskiness of the project, coupled with the macro-economic exposure (as measured by covariance of returns with the broader capital asset market) inherent in the operations of the plant. Based on this information, a 15% discount is exceptionally conservative and reflects a high degree of uncertainty in the operations of the proposed plant, consistent with a plant in the first stages of design. Using this conservative discount rate, the process is expected to deliver a net present value of $35.2 million, over an assumed 20 year design life. This value and the cash flow in each period used to calculate it are summarized in Table 26.

Another measure of economic attractiveness, though not as ideal as NPV, is the Internal Rate of Return (IRR). The IRR is defined as that discount rate at which the NPV of a series of cash flows is zero. In a way then, this can be thought of as the annual return on an investment in the plant. The IRR must be calculated as the root of n^{th} degree polynomial, where n is the project life of the investment in years. This mathematical misbehavior makes IRR a sometimes unreliable investment decision criterion. In our case the IRR of the proposed plant was 17.56% reflecting a reasonably high possible return and suggesting that the profitability of the project is attractive enough to warrant significant further study.

The NPV of the process is of course dependent on a variety of operating assumptions, independent of the basic product, feedstock and equipment economics. In particular the assumptions made regarding the working capital requirements of the proposed plant represent a significant driver of early year cash flow, and due to the time value of money, represent a significant amount of the overall NPV. Working capital in our analysis consisted of accounts receivable, cash reserves, accounts payable, product inventory and raw material inventory. Accounts receivable was estimated as equivalent to 30 days of sales. Cash reserves were estimated using a 30 day cash cycle assumption (using the difference in receivables and payables). Accounts payable are assumed to be equivalent to 30 days worth of raw material costs. Inventory estimates assume a 4 day storage cycle for acrylic acid product and a 2 day storage cycle for the raw materials (including corn, nutrient media, phosphoric acid, CO_2 and process water). For the purpose of NPV calculations, it is assumed that the working capital is accumulated over three years during full design and plant construction, with 50% contribution in the first year and 25% in each subsequent year. This schedule with each line item estimate is summarized in the Fixed Capital investment section of the report, specifically Table 23.

Cash Flow and NPV Summary

Year	**2013**	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**	**2020**	**2021**	**2022**
Design Capacity	*0%*	*0%*	*45%*	*68%*	*90%*	*90%*	*90%*	*90%*	*90%*	*90%*
Revenue	$ -	$ -	$ 230,400,000	$ 345,600,000	$ 460,800,000	$ 460,800,000	$ 460,800,000	$ 460,800,000	$ 460,800,000	$ 460,800,000
Less: Capital Cost	-	(266,807,506)	-	-	-	-	-	-	-	-
Less: Working Capital Contribution	-	(12,724,000)	(6,362,000)	(6,362,000)	-	-	-	-	-	-
Less: Variable Costs	-	-	(177,058,827)	(265,588,240)	(354,117,653)	(354,117,653)	(354,117,653)	(354,117,653)	(354,117,653)	(354,117,653)
Less: Fixed Costs	-	-	(24,492,393)	(24,492,393)	(24,492,393)	(24,492,393)	(24,492,393)	(24,492,393)	(24,492,393)	(24,492,393)
Less: Depreciation	-	-	(41,429,737)	(66,287,579)	(39,772,547)	(23,863,528)	(23,863,528)	(11,931,764)	-	-
Pre-Tax Net Income	$ -	$ -	$ (12,580,957)	$ (10,768,212)	$ 42,417,406	$ 58,326,425	$ 58,326,425	$ 70,258,189	$ 82,189,953	$ 82,189,953
Less: Taxes	-	-	4,654,954	3,984,239	(15,694,440)	(21,580,777)	(21,580,777)	(25,995,530)	(30,410,283)	(30,410,283)
Net Income	$ -	$ -	$ (7,926,003)	$ (6,783,974)	$ 26,722,966	$ 36,745,648	$ 36,745,648	$ 44,262,659	$ 51,779,671	$ 51,779,671
Free Cash Flow	$ -	$ (279,531,500)	$ 27,141,800	$ 53,141,600	$ 66,495,500	$ 60,609,200	$ 60,609,200	$ 56,194,400	$ 51,779,700	$ 51,779,700
Net Present Value	$ -	$ (243,070,837)	$ (222,547,771)	$ (187,606,289)	$ (149,587,263)	$ (119,453,791)	$ (93,250,771)	$ (72,125,206)	$ (55,198,340)	$ (40,479,326)

Year	**2023**	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**	**2031**	**2032**
Design Capacity	*90%*	*90%*	*90%*	*90%*	*90%*	*90%*	*90%*	*90%*	*90%*	*90%*
Revenue	$ 460,800,000	$ 460,800,000	$ 460,800,000	$ 460,800,000	$ 460,800,000	$ 460,800,000	$ 460,800,000	$ 460,800,000	$ 460,800,000	$ 460,800,000
Less: Capital Cost	-	-	-	-	-	-	-	-	-	-
Less: Working Capital Contribution	-	-	-	-	-	-	-	-	-	25,447,900
Less: Variable Costs	(354,117,653)	(354,117,653)	(354,117,653)	(354,117,653)	(354,117,653)	(354,117,653)	(354,117,653)	(354,117,653)	(354,117,653)	(354,117,653)
Less: Fixed Costs	(24,492,393)	(24,492,393)	(24,492,393)	(24,492,393)	(24,492,393)	(24,492,393)	(24,492,393)	(24,492,393)	(24,492,393)	(24,492,393)
Less: Depreciation	-	-	-	-	-	-	-	-	-	-
Pre-Tax Net Income	$ 82,189,953	$ 82,189,953	$ 82,189,953	$ 82,189,953	$ 82,189,953	$ 82,189,953	$ 82,189,953	$ 82,189,953	$ 82,189,953	$ 82,189,953
Less: Taxes	(30,410,283)	(30,410,283)	(30,410,283)	(30,410,283)	(30,410,283)	(30,410,283)	(30,410,283)	(30,410,283)	(30,410,283)	(30,410,283)
Net Income	$ 51,779,671	$ 51,779,671	$ 51,779,671	$ 51,779,671	$ 51,779,671	$ 51,779,671	$ 51,779,671	$ 51,779,671	$ 51,779,671	$ 51,779,671
Free Cash Flow	$ 51,779,700	$ 51,779,700	$ 51,779,700	$ 51,779,700	$ 51,779,700	$ 51,779,700	$ 51,779,700	$ 51,779,700	$ 51,779,700	$ 77,227,600
Net Present Value	$ (27,680,183)	$ (16,550,494)	$ (6,872,503)	$ 1,543,141	$ 8,861,092	$ 15,224,528	$ 20,757,951	$ 25,569,623	$ 29,753,685	$ 35,180,106

Final Year Net Present Value **$ 35,180,106**

Table 26. Cash Flow and NPV Summary

Economic Sensitivities

The economic attractiveness of the proposed process is subject to a number of assumptions which are impossible to accurately predict and which are subject to significant variability. Every attempt was made throughout the calculation of the measures of economic attractiveness to use conservative assumptions, however due to unpredictability within various significant drivers of the process economics it is necessary to present NPV and IRR over a range of possible variables for the process economics.

Product Price – Given the specified plant capacity, the assumed product price is the sole driver of overall process revenue. Thus, the product price is of significant importance to the sensitivity analysis of the process economics. As will be seen, given base case assumptions, a swing of ±$.05/kg in the price of acrylic acid results in a corresponding swing of approximately ±$19 million of NPV. Based on market research, the price of acrylic has varied significantly in recent years, putting significant revenue risk on the economic viability of the process.[23]

Corn Price – Based on the base case plant location, the US Midwest, corn forms the basic carbohydrate source for the process and is processed to provide glucose to the fermentation tanks in the required amounts. It is assumed, per the original problem statement, that the processed corn is provided to the proposed plant at the market price of corn, which is subject to significant variability due to seasonality, weather patterns, harvest quality and quantity and a host of other unpredictable factors. For the purposes of base case assumptions, the price of corn ($/kg) was assumed to be $.28.[24] For the purposes of sensitivity analysis, this price was assumed to vary

[23] [53] Mirasol
[24] [32] Maize (corn) daily price

between $.22 and $.34 / kg. A summary of the effects on the NPV of the process by assumed product price and corn price (both in $/kg) is shown in Table 27.

NPV Sensitivities								
		Product Price						
		$ 3.05	3.10	3.15	3.20	3.25	3.30	3.35
Corn Cost ($/kg)	$ 0.22	23,387,100	42,108,300	60,829,500	79,550,800	98,272,000	116,993,200	135,714,400
	0.24	8,596,900	27,318,100	46,039,300	64,760,500	83,481,800	102,203,000	120,924,200
	0.26	(6,193,400)	12,527,900	31,249,100	49,970,300	68,691,600	87,412,800	106,134,000
	0.28	(20,983,600)	(2,262,400)	16,458,900	35,180,100	53,901,300	72,622,600	91,343,800
	0.30	(35,773,800)	(17,052,600)	1,668,700	20,389,900	39,111,100	57,832,300	76,553,600
	0.32	(50,564,000)	(31,842,800)	(13,121,600)	5,599,700	24,320,900	43,042,100	61,763,400
	0.34	(65,354,200)	(46,633,000)	(27,911,800)	(9,190,500)	9,530,700	28,251,900	46,973,100

Table 27. NPV Sensitivity Analysis (Acrylic Acid vs. Corn Price)

Media – Because of the proposed process' high nutrient requirements for effective fermentation, and because of the non-renewability of the component, the media is a large raw material requirement for the proposed process. It also has a relatively high cost at $4.57/kg (based on industrial scale adjustments).[25] Because of the high raw material and relatively high cost, the overall economic feasibility of the proposed process is highly dependent on the assumed price of media at an industrial scale. It is also possible that alternative nutrient sources could reduce or eliminate the media requirement of the process. Laboratory scale fermentation with the particular *E. coli* strain used in the proposed process would allow a clearer determination of the process' feasibility and overall sensitivity to the price of the media. It is worth noting that, since the media cost (summarized in Table 24) is so high relative to other variable costs, elimination or reduction of the overall nutrient requirement of the process would have significantly positive effects on the economic feasibility of the project. The overall sensitivity of the process NPV to the media price (assuming base case nutrient requirements) is summarized in Table 28. As can be seen from this table, a ±$.50/kg swing in the price of media results in a total process NPV swing of approximately ±$57 million. Clearly, any process modification which can reduce the nutrient

[25] Based on suggestions Mr. Bruce Vrana

requirements of the fermentation, or reduce their effective price, can significantly increase the economic attractiveness of the project. As discussed before, this profit potential strongly justifies further research into the nutrient requirements of the fermentation process.

NPV Sensitivities								
		Product Price						
		$ 2.90	3.00	3.10	3.20	3.30	3.40	3.50
Media Price ($/kg)	$ 3.00	103,741,500	141,184,000	178,626,400	216,068,900	253,511,300	290,953,800	328,396,300
	3.50	46,133,600	83,576,100	121,018,500	158,461,000	195,903,500	233,345,900	270,788,400
	4.00	(11,474,300)	25,968,200	63,410,600	100,853,100	138,295,600	175,738,000	213,180,500
	4.50	(69,082,200)	(31,639,700)	5,802,800	43,245,200	80,687,700	118,130,100	155,572,600
	5.00	(126,690,100)	(89,247,600)	(51,805,100)	(14,362,700)	23,079,800	60,522,200	97,964,700
	5.50	(184,297,900)	(146,855,500)	(109,413,000)	(71,970,600)	(34,528,100)	2,914,300	40,356,800
	6.00	(241,905,800)	(204,463,400)	(167,020,900)	(129,578,500)	(92,136,000)	(54,693,500)	(17,251,100)

Table 28. NPV Sensitivity Analysis (Product Price vs. Media)

Waste Water Treatment – The cost of waste water treatment is a significant utility cost for the proposed process and is necessary to minimize the environmental impact of the plant. As discussed in the operating costs section of the report, the tradeoff between steam utility costs and waste water treatment costs was explored in detail and optimized using base case cost assumptions. The cost of waste water treatment regardless has a significant effect on the annual operating costs of the overall process and therefore on the overall economic feasibility of the process. This sensitivity is shown directly in Table 29. As can be seen, at base case assumptions a ±$.10 / kg organic removed in waste water treatment costs results in a roughly ±$6 million swing in the NPV of the process.

NPV Sensitivities								
		Product Price						
		$ 3.05	3.10	3.15	3.20	3.25	3.30	3.35
Waste Water Treatment ($/kg Organic)	$ 0.05	(3,065,300)	15,656,000	34,377,200	53,098,400	71,819,600	90,540,900	109,262,100
	0.15	(9,464,700)	9,256,600	27,977,800	46,699,000	65,420,200	84,141,500	102,862,700
	0.25	(15,864,100)	2,857,200	21,578,400	40,299,600	59,020,900	77,742,100	96,463,300
	0.35	(22,263,500)	(3,542,200)	15,179,000	33,900,200	52,621,500	71,342,700	90,063,900
	0.45	(28,662,900)	(9,941,600)	8,779,600	27,500,800	46,222,100	64,943,300	83,664,500
	0.55	(35,062,200)	(16,341,000)	2,380,200	21,101,400	39,822,700	58,543,900	77,265,100
	0.65	(41,461,600)	(22,740,400)	(4,019,200)	14,702,000	33,423,300	52,144,500	70,865,700

Table 29. NPV Sensitivity Analysis (Product Price vs. Waste Water)

High Pressure (150 psig) Steam – The largest utility cost for the process is the cost of high pressure (150 psig) steam. The steam is primarily used to drive the separation (evaporation and distillation) sections of the process. A better (more efficient) separation of the components is possible, but would result in dramatically higher steam utility costs (due to the high amount of water present within the process). Also of concern is the volatile price of energy over time. Most steam in the US is generated in fossil fuel fired furnaces and relies on fossil fuels (such as coal) as a power source. Recent events have demonstrated that energy and fuel markets can be volatile and it is not unreasonable to consider the possibility that world events result in significantly increased energy costs in the US. Higher energy prices would directly translate into high utility prices of steam, which given the high steam requirements of the process, could materially affect the proposed process' economic attractiveness. The explicit effect of steam price (listed per 1000 kg) on the process' NPV is shown in Table 30. As seen in this table, a ±$1/1000 kg swing in the price of high pressure steam results in a greater than ±$19 million swing in NPV of the process.

NPV Sensitivities

150 psig Steam Price ($/1000 kg)	Product Price: $ 3.11	3.14	3.17	3.20	3.23	3.26	3.29
$ 4.50	58,966,000	70,198,800	81,431,500	92,664,200	103,897,000	115,129,700	126,362,500
6.50	39,804,700	51,037,400	62,270,100	73,502,900	84,735,600	95,968,300	107,201,100
8.50	20,643,300	31,876,000	43,108,700	54,341,500	65,574,200	76,807,000	88,039,700
10.50	1,481,900	12,714,600	23,947,400	35,180,100	46,412,800	57,645,600	68,878,300
12.50	(17,679,500)	(6,446,700)	4,786,000	16,018,700	27,251,500	38,484,200	49,716,900
14.50	(36,840,900)	(25,608,100)	(14,375,400)	(3,142,700)	8,090,100	19,322,800	30,555,600
16.50	(56,002,200)	(44,769,500)	(33,536,800)	(22,304,000)	(11,071,300)	161,400	11,394,200

Table 30. NPV Sensitivity Analysis (Product Price vs. Steam Price)

In addition to the specific highly significant factors which affect project profitability discussed above, the high level factors which affect economic feasibility include total permanent investment, fixed costs and variable costs. The sensitivity of the project IRR to these factors is summarized in Table 31. As expected, higher initial investment results in significantly lowered IRR, as does increased fixed and variable cost. In contrast, high product price results in significantly increased process IRR. This trend is seen throughout the IRR sensitivity tables. It is worth noting that the product price can vary significantly across most of the other variables while still maintaining reasonably high IRR values suggesting strong profitability potential within the project.

IRR Sensitivity

		Product Price						
		$ 2.72	2.88	3.04	3.20	3.36	3.52	3.68
Variable Costs	$ 275,424,841	25.38%	29.47%	33.35%	37.05%	40.61%	44.05%	47.39%
	314,771,247	18.27%	22.85%	27.07%	31.04%	34.81%	38.42%	41.91%
	354,117,653	9.87%	15.43%	20.25%	24.63%	28.70%	32.55%	36.22%
	393,464,059	Negative IRR	6.25%	12.43%	17.56%	22.12%	26.32%	30.26%
	432,810,465	Negative IRR	Negative IRR	2.04%	9.18%	14.74%	19.54%	23.90%
	472,156,871	Negative IRR	Negative IRR	Negative IRR	Negative IRR	5.56%	11.75%	16.87%
	511,503,277	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR	1.35%	8.50%

IRR Sensitivity

		Product Price						
		$ 2.72	2.88	3.04	3.20	3.36	3.52	3.68
Fixed Costs	$ 17,144,675	0.92%	8.58%	14.36%	19.31%	23.76%	27.89%	31.78%
	19,593,915	Negative IRR	7.82%	13.73%	18.73%	23.22%	27.37%	31.27%
	22,043,154	Negative IRR	7.05%	13.08%	18.15%	22.67%	26.85%	30.77%
	24,492,393	Negative IRR	6.25%	12.43%	17.56%	22.12%	26.32%	30.26%
	26,941,633	Negative IRR	5.43%	11.76%	16.97%	21.57%	25.80%	29.76%
	29,390,872	Negative IRR	4.59%	11.09%	16.37%	21.02%	25.27%	29.25%
	31,840,111	Negative IRR	3.72%	10.41%	15.77%	20.47%	24.75%	28.74%

IRR Sensitivity

		Product Price						
		$ 2.72	2.88	3.04	3.20	3.36	3.52	3.68
Total Permanent Investment	$ 186,765,254	8.11%	18.84%	27.38%	34.92%	41.85%	48.35%	54.52%
	213,446,004	3.92%	13.68%	21.14%	27.61%	33.50%	39.00%	44.21%
	240,126,755	Negative IRR	9.60%	16.31%	22.00%	27.13%	31.89%	36.38%
	266,807,506	Negative IRR	6.25%	12.43%	17.56%	22.12%	26.32%	30.26%
	293,488,256	Negative IRR	3.43%	9.22%	13.94%	18.08%	21.85%	25.36%
	320,169,007	Negative IRR	0.98%	6.51%	10.92%	14.73%	18.17%	21.35%
	346,849,757	Negative IRR	Negative IRR	4.17%	8.34%	11.90%	15.08%	18.00%

Table 31. IRR Sensitivity Analysis

As discussed in the Total Equipment List section of the report on page 70, a significant portion of the total bare module costs of the proposed design comes from the cost of the installed process fermenters (contributing roughly $77 million to the total bare module costs of the process). This exceptionally high cost arises from the required volume of the fermenters, which is subject to a number of assumptions which are difficult to verify without experimental data. Specifically, variations in the batch time and maximum concentration of 3-HP in the fermentation broth strongly affect the required size of the process fermenters. The base case assumptions for the process are a batch time of 31 hours and a maximum 3-HP content of 9.25% by mass in the final fermentation broth. An analysis of the expected change in bare module costs from the base case, subject to different assumptions of batch time and maximum possible 3-HP concentration is shown in Table 32.

% Variation in Fermenter Bare Module Costs

Maximum 3-HP Content	Batch Time (hours) → 28	29	30	31	32	33	34
8.0%	9.6%	11.4%	13.2%	14.9%	24.2%	26.0%	27.7%
9.0%	(3.4%)	(1.8%)	(0.3%)	1.3%	10.4%	12.0%	13.6%
10.0%	(15.3%)	(13.9%)	(5.0%)	(3.6%)	(2.1%)	(0.7%)	0.7%
11.0%	(19.0%)	(17.6%)	(16.3%)	(15.0%)	(13.8%)	(5.0%)	(3.7%)
12.0%	(29.4%)	(28.3%)	(19.6%)	(18.4%)	(17.2%)	(16.0%)	(14.8%)
13.0%	(32.0%)	(30.9%)	(29.8%)	(28.7%)	(27.6%)	(19.1%)	(17.9%)
14.0%	(34.3%)	(33.2%)	(32.2%)	(31.1%)	(30.1%)	(29.1%)	(28.1%)
15.0%	(43.5%)	(42.6%)	(34.3%)	(33.3%)	(32.3%)	(31.3%)	(30.4%)

Table 32. Fermenter Bare Module Costs Sensitivity

Location Selection

The location of the proposed process is a topic to which considerable effort has been expended. The two available locations are Brazil and the US Midwest. If the Midwest is selected, corn is available as a renewable feedstock, while Brazil's available feedstock is molasses and cane juice from sugarcane harvesting. Cane juice / molasses is significantly cheaper than corn, however has a much lower usable carbohydrate content by mass and hence requires significantly increased amounts of raw material. Additionally, due to seasonality and time limits on the storage of cane juice / molasses, operation in Brazil can only continue for at most 9 months out of the year. This requires any equipment built in Brazil to be able to handle roughly 30% more capacity than an equivalent process in the US. This increase in required investment is slightly offset by the difference in assumed site factors for the two locations. The US Midwest has an assumed site factor of 1.15 compared to 1.00 for Brazil, meaning that the total permanent investment in the US is increased 15% relative to Brazil, *ceteris paribus*.[26] Taking this increased investment into account as well as the difference in raw material amount and processing over the estimated 20 year design life of the plant allows calculation of the difference in the NPV between the US case and the Brazil case. This analysis assumed that the usable carbohydrate in sugar cane juice is 9% by mass and 82% by mass in corn. It also assumed a 37% effective tax rate and a 5 year MACRS depreciation schedule for both jurisdictions.[27] The results of this analysis revealed that the NPV difference between the two jurisdictions was exceptionally sensitive to the assumed price of cane juice / molasses in Brazil. Sources indicate that the going price of cane juice in Brazil is around \$.02 - \$.025/ kg.[28] However, due to highly volatile prices in recent weeks and months, it is unreasonable to simply assume a price and do a single analysis to make a location decision.

[26] Table 22.13 – pg. 552, Product and Process Design Principles, 3rd Edition
[27] [54] "Brazil Tax Rates"
[28] [25] Kiernan

Instead, the decision was made to conduct a sensitivity analysis and observe the empirical spread of marginal NPV between the two locations based on cane juice price and an increase in total permanent investment (relative to the US case). A summary of this analysis is shown in Table 33.

Brazil vs. US Midwest Sensitivity								
		% Increase in Total Permanent Investment						
		10.0%	15.0%	20.0%	25.0%	30.0%	35.0%	40.0%
Cane Juice Price ($/kg)	$ 0.003	180,741,211	166,900,565	153,059,920	139,219,274	125,378,629	111,537,983	97,697,338
	0.010	125,371,950	111,531,304	97,690,659	83,850,013	70,009,368	56,168,722	42,328,077
	0.018	70,002,689	56,162,044	42,321,398	28,480,753	14,640,107	799,462	(13,041,184)
	0.025	14,633,429	792,783	(13,047,863)	(26,888,508)	(40,729,154)	(54,569,799)	(68,410,445)
	0.033	(40,735,832)	(54,576,478)	(68,417,123)	(82,257,769)	(96,098,414)	(109,939,060)	(123,779,705)
	0.040	(96,105,093)	(109,945,739)	(123,786,384)	(137,627,030)	(151,467,675)	(165,308,321)	(179,148,966)
	0.048	(151,474,354)	(165,314,999)	(179,155,645)	(192,996,290)	(206,836,936)	(220,677,581)	(234,518,227)

Table 33. Location Selection Analysis

As can be seen, the marginal NPV is hugely sensitive to the assumed priced of cane juice. Cane juice price has also shown significant variability over time, being on both ends of the explored range at various times in recent years. This uncertainty, even independent of the expected investment increase suggests to the design team that the US Midwest location would be most advantageous. Note that the marginal NPV of the Brazil case is in many cases much larger than the expected NPV of the US case, suggesting a strong and unpredictable possibility that an adverse move in sugar cane juice prices could remove all economic feasibility from the project if the Brazil location were selected. In contrast, the US corn market has shown relative stability in recent years, though admittedly with a clear upward trend. Thus, it was determined that the Brazil location represented too much volatility in terms of economic returns to be a feasible option for the process. The US Midwest location is thus used as the assumed location of the proposed plant.

Conclusions and Recommendations

The report contained herein is an exciting and comprehensive first look at the economic and scientific viability of using renewable carbohydrate sources in a large scale carbon-neutral commodity chemical production. The design team estimates that the project will deliver an NPV of $35.2 MM over 20 years, at an IRR of 17.56% using the base case estimates detailed within the report. We recommend that the plant be located in the US Midwest, with ready access to corn and in partnership with the discussed corn-dry grind partner plant. This location offers cost predictability and substantial infrastructure advantages over alternatives available using cane juice / molasses in Brazil. The process does contain certain risks to profitability, including substantial rises in energy and utility costs, as well as unanticipated rises in raw material costs. However, the process also has substantial upside potential due to scientific uncertainty as to the fermentation nutrient requirements. Laboratory level data could alleviate these uncertainties at minimal cost and confirm the enormous profitability potential of this process, especially due to the ubiquity of *E. coli* in research laboratories throughout the country.

Because of high utility costs, it may also be worthwhile exploring alternative separation techniques, specifically mass separating agents, or using alternative micro-organisms which can produce higher than anticipated concentrations of intermediate product via fermentation to decrease the amount of water separation required throughout the process.

Overall, the design team finds the proposed process to be very worthy of additional significant and detailed research. The use of renewable carbon sources in chemical production is most assuredly a burgeoning industry and offers significant economic potential to the exploring company.

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Appendix

Appendix I - Problem Statement

8. Renewable Acrylic Acid
(recommended by Stephen M. Tieri, DuPont)

As a result of climate change, dwindling petroleum resources, material pricing volatility, and the desire for energy independence, there has been significant research and investment in the last decade to develop technologies that reduce energy consumption, improve efficiency, and produce materials and fuels from renewable resources. Government grants and subsidies as well as consumer demand are driving the intense industrial and academic competition to develop bio-based and sustainable materials – with equivalent functionality to the traditional petrochemical derived materials, but derived from renewable sources and with reduced environmental burden.

Acrylic acid is an important building block in the production of many industrial and consumer products, and existing producers have been investing heavily on R&D resources to produce acrylic acid from renewable raw materials. Most acrylic acid is consumed in polymer form, either directly or after synthesis of an acrylic ester. The acrylic esters are, in turn, consumed as co-monomers, which when polymerized are used in paints, textiles, coatings, adhesives, and plastics. Acrylic acid is also polymerized to produce polyacrylic acid-based polymers that are used in super-absorbents, detergents, dispersants, flocculants, and thickeners.

Through its research efforts, your company has developed new and innovative technologies to produce acrylic acid, through conversion of biomass-derived and renewable feedstocks, rather than crude oil or natural gas. Specifically, a research group developed a microorganism (bacteria) which is the catalyst and basis for this bio-based production route to 3-hydroxypropionic acid, which can subsequently be transformed into acrylic acid. As the acrylic acid has the identical structure and functionality of traditional petrochemical based acrylic acid, it serves as a direct replacement to produce renewably sourced polymers without modifications to downstream equipment or processes. Early developmental successes resulted in supplemental research funding awarded through several government grants, which have provided partial funding for the development and pilot-production programs.

The microorganism and process have been tested across a variety of commercial feedstocks, with no apparent loss in key fermentation performance metrics or final product quality. Successful pilot trials over the past several years produced material from both 200 L and 20,000 L fermentation vessels, and purified it to greater than 99%. Results from pilot-plant operation indicated that product yield, microbiological productivity, separation, and purification, were on-target to deliver cost advantages at commercial scale. Now that the research, development, and pilot teams have succeeded in achieving their milestone targets, corporate leadership is confident in proceeding to the first commercial-scale production facility. When complete, it is expected that this bacteria-based process will produce 75 percent fewer carbon-dioxide emissions than when generating product from oil. Your project team has been assembled to design the first commercial plant for this new sustainable technology. The business objective is to design a commercial-scale facility to produce 160,000 MT/yr (metric tons per year) of acrylic acid from a renewable sugar feedstock. The acrylic acid product purity and quality will need to meet or exceed current commercial requirements for polymer grade material, to be acceptable to perspective customers.

As a result of successful collaborations, your company negotiated an agreement with a world leader in agricultural processing to supply sugar to the plant and process for this program. The bio-acrylic acid manufacturing facility will be co-located on a site with one of the partner's existing facilities. Based on your input, the partner will expand either one of its ethanol dry mills in the Midwestern United States, or one of its sugar and ethanol facilities in Brazil to provide sufficient sugar capacity to meet the acrylic acid process requirements. Starch/sugar/carbohydrate supply from the dry mill is expected to be typical of that currently used to supply fuel ethanol fermentations, while the Brazilian facility will supply molasses and cane juice at standard cane industry concentrations. The project includes the design and sizing of the additional biomass processing systems, sugar extraction/concentration processes, and biomass storage facilities. This is necessary to assure that your partner provides a consistent raw-material supply to your new process. However, your company will not be responsible for direct operation of the biomass to sugar conversion equipment and facilities. The acrylic acid plant is expected to have some onsite storage for the 3-hydroxypropionic acid intermediate and final acrylic acid product at a minimum. In addition to raw material economics, your team will need to consider carefully the advantages, disadvantages, potential obstacles, and restrictions for each sugar supply option when making its selection; for example, the sugar-cane crushing season in Brazil is 8-9 months long.) Current market pricing is to be expected for all raw materials, utilities, and product, regardless of location.

Your company intends to use this technology to attract additional investors, industrial partners for both feedstock supply and sustainably branded intermediates and polymers. Your company expects to build and operate this commercial facility, in addition to some future sister facilities, and does not currently plan to license this technology as an additional revenue source. However, your corporate marketing group plans to advertize this technology as a successful example of your company's capability to achieve smaller process and product costs for building and manufacturing, compared to conventionally produced acrylic acid. Additionally, there is a business target for this commercial process to produce bio-acrylic acid 50 cents/lb lower than conventional hydrocarbon-based acrylic acid.

Your plant design is expected to be as environmentally friendly as possible, and to satisfy state and federal emissions legislation. It is expected that the facility will include emission-control equipment as a part of the process design. You should recover and recycle process materials to the maximum economic extent. Also, energy consumption should be minimized, to the extent economically justified – and he plant design must be controllable and safe to operate. As the process technology integration and design team, you will participate in the start-up and will have to live with any of your poor design decisions.

You will need additional data beyond that given here and listed in the references below. Cite any literature data used. If required, make reasonable assumptions, state them, especially when your design operation or economics are sensitive to the assumptions you made.

Appendix II – Aspen Input / Report Summary

Input Summary

```
DYNAMICS
    DYNAMICS RESULTS=ON

IN-UNITS ENG

OUT-UNITS ENG

DEF-STREAMS CONVEN ALL

SIM-OPTIONS MASS-BAL-CHE=YES OLD-DATABANK=YES

DATABANKS PURE25  / AQUEOUS  / SOLIDS  / INORGANIC  /  &
        NOASPENPCD

PROP-SOURCES PURE25  / AQUEOUS  / SOLIDS  / INORGANIC

COMPONENTS
    WATER H2O /
    ACRYL-01 C3H4O2-1 /
    3HP C3H6O3-D1 /
    H3PO4 H3PO4 /
    CO2 CO2

HENRY-COMPS HC-1 CO2

CHEMISTRY C-1
    STOIC 1 3HP -1. / ACRYL-01 1. / WATER 1.

FLOWSHEET
    BLOCK R-101 IN=SR-104 SR-101 SR-133 RXHT OUT=SR-105 2
    BLOCK D-101 IN=SR-142A SR-105 OUT=SR-111A SR-112A
    BLOCK D-102 IN=SD-101 OUT=SR-130 SR-118
    BLOCK S-102 IN=SR-130 OUT=SR-131 SR-132
    BLOCK D-103 IN=SD-109 OUT=SR-140 SR-125
    BLOCK M-103 IN=SR-131 SR-141 OUT=SR-129
    BLOCK S-101 IN=SR-125 OUT=SR-126A SR-127
    BLOCK M-102 IN=SR-103 SR-149A OUT=SR-104
    BLOCK PE-101 IN=S-E101 OUT=S-E102
    BLOCK PE-103 IN=S-E112 OUT=SR-101
    BLOCK PD-107 IN=SR-126A OUT=SR-149A
    BLOCK PR-101 IN=SR-102 OUT=SR-103
    BLOCK P-105 IN=SR-132 OUT=SR-133
    BLOCK FE-101 IN=S-E102 OUT=S-E103 S-E104
    BLOCK FE-102 IN=S-E104 H1 OUT=S-E105 S-E106
    BLOCK FE-103 IN=S-E106 H2 OUT=S-E107 S-E108 XSH3
```

```
    BLOCK FE-104 IN=S-E108 H3 OUT=S-E109 S-E110 XSH4
    BLOCK FE-105 IN=S-E110 H4 OUT=S-E111 S-E112 XSH5
    BLOCK HX-101 IN=S-E103 OUT=S-E113 H1
    BLOCK HX-102 IN=S-E105 OUT=S-E114 H2
    BLOCK HX-103 IN=S-E107 OUT=S-E115 H3
    BLOCK HX-104 IN=S-E109 OUT=S-E116 H4
    BLOCK HX-105 IN=S-E111 OUT=S-E123 XSH6
    BLOCK M-101 IN=S-E113 S-E114 S-E115 S-E116 S-E123 OUT= &
        S-E125A
    BLOCK HX-109 IN=S-E118 XSH6 OUT=S-E119
    BLOCK HX-110 IN=SR-140 OUT=SR-141 RXHT
    BLOCK HX-108 IN=S-E119 XSH5 OUT=S-E120
    BLOCK HX-107 IN=S-E120 XSH4 OUT=S-E121
    BLOCK HX-106 IN=S-E121 XSH3 OUT=WASTE
    BLOCK PE-102 IN=S-E117 OUT=S-E118
    BLOCK PD-101 IN=SR-112A OUT=SD-101
    BLOCK PD-104 IN=SR-118 OUT=SD-109

PROPERTIES NRTL
    PROPERTIES NRTL-2

PROP-DATA PCES-1
    IN-UNITS ENG
    PROP-LIST RKTZRA / VLSTD
    PVAL H3PO4 .2917801570 / .8363143655

PROP-DATA PLXANT-1
    IN-UNITS ENG PRESSURE=torr TEMPERATURE=C PDROP=psi
    PROP-LIST PLXANT
    PVAL 3HP 21.15739523 -6049.213401 198.6

PROP-DATA SIGDIP-1
    IN-UNITS ENG
    PROP-LIST SIGDIP
    PVAL H3PO4 102.8207450 1.222222220 -7.070789E-10  &
        7.8902008E-10 -3.166124E-10 764.3299979 1357.249993

PROP-DATA HENRY-1
    IN-UNITS ENG
    PROP-LIST HENRY
    BPVAL CO2 WATER 175.2762325 -15734.78987 -21.66900000  &
        6.12550005E-4 31.73000375 175.7300026 0.0

PROP-DATA NRTL-1
    IN-UNITS ENG TEMPERATURE=K
    PROP-LIST NRTL
```

```
    BPVAL WATER 3HP 4.22774992 -749.350017 .3 0.0 0.0 0.0  &
        0.0 1000.000
    BPVAL 3HP WATER -2.53298289 641.907787 .3 0.0 0.0 0.0  &
        0.0 1000.000
    BPVAL ACRYL-01 3HP 0 24.90302930 .3000000 0.0 0.0 0.0  &
        0.0 1000.000
    BPVAL 3HP ACRYL-01 0 -53.26251030 .3000000 0.0 0.0 0.0  &
        0.0 1000.000

PROP-DATA NRTL-1
    IN-UNITS ENG
    PROP-LIST NRTL
    BPVAL WATER ACRYL-01 0.0 1676.270867 .3000000000 0.0 0.0  &
        0.0 212.7200023 248.9000020
    BPVAL ACRYL-01 WATER 0.0 -543.5965757 .3000000000 0.0 0.0  &
        0.0 212.7200023 248.9000020

PROP-DATA NRTL-2
    IN-UNITS ENG
    PROP-LIST NRTL 2
    BPVAL WATER ACRYL-01 0.0 1676.270867 .3000000000 0.0 0.0  &
        0.0 212.7200023 248.9000020
    BPVAL ACRYL-01 WATER 0.0 -543.5965757 .3000000000 0.0 0.0  &
        0.0 212.7200023 248.9000020

STREAM S-E101
    SUBSTREAM MIXED TEMP=37. <C> PRES=1. <atm>  &
        MASS-FLOW=330296.76 <kg/hr>
    MASS-FRAC WATER 0.9075 / ACRYL-01 0. / 3HP 0.0925 /  &
        H3PO4 0. / CO2 0.

STREAM S-E117
    IN-UNITS MET
    SUBSTREAM MIXED TEMP=25. <C> PRES=1. MASS-FLOW=103000.
    MASS-FRAC WATER 1.

STREAM S-E118
    IN-UNITS MET
    SUBSTREAM MIXED TEMP=25. <C> PRES=1.1 MOLE-FLOW=5900.
    MASS-FRAC WATER 1.

STREAM SR-102
    IN-UNITS MET
    SUBSTREAM MIXED TEMP=25. <C> PRES=1. MASS-FLOW=10.
    MASS-FLOW H3PO4 50.
```

```
STREAM SR-142A
   IN-UNITS MET
   SUBSTREAM MIXED TEMP=100. <C> PRES=10. <bar> MASS-FLOW=1.
   MASS-FRAC CO2 1.

DEF-STREAMS HEAT 2

DEF-STREAMS HEAT H1

DEF-STREAMS HEAT H2

DEF-STREAMS HEAT H3

DEF-STREAMS HEAT H4

DEF-STREAMS HEAT RXHT

DEF-STREAMS HEAT XSH3

DEF-STREAMS HEAT XSH4

DEF-STREAMS HEAT XSH5

DEF-STREAMS HEAT XSH6

BLOCK M-101 MIXER
   IN-UNITS MET
   PARAM PRES=1.

BLOCK M-102 MIXER
   IN-UNITS MET
   PARAM PRES=5.1 <bar>

BLOCK M-103 MIXER
   IN-UNITS MET
   PARAM PRES=1.

BLOCK S-101 FSPLIT
   IN-UNITS MET
   PARAM PRES=1.1
   FRAC SR-126A 0.99

BLOCK S-102 FSPLIT
   IN-UNITS MET
   PARAM PRES=1.1
   FRAC SR-131 0.01
```

```
BLOCK HX-101 HEATER
    IN-UNITS MET
    PARAM TEMP=294.3 <F> PRES=4.9

BLOCK HX-102 HEATER
    IN-UNITS MET
    PARAM TEMP=278.6 <F> PRES=3.9

BLOCK HX-103 HEATER
    IN-UNITS MET
    PARAM TEMP=259.8 <F> PRES=2.9

BLOCK HX-104 HEATER
    IN-UNITS MET
    PARAM TEMP=120. <C> PRES=1.95

BLOCK HX-105 HEATER
    IN-UNITS MET
    PARAM TEMP=95. <C> PRES=1.

BLOCK HX-106 HEATER
    IN-UNITS MET
    PARAM PRES=2.2

BLOCK HX-107 HEATER
    IN-UNITS MET
    PARAM PRES=2.3

BLOCK HX-108 HEATER
    IN-UNITS MET
    PARAM PRES=2.4

BLOCK HX-109 HEATER
    IN-UNITS MET
    PARAM PRES=2.5

BLOCK HX-110 HEATER
    IN-UNITS MET
    PARAM TEMP=140. <C> PRES=1.

BLOCK FE-101 FLASH2
    IN-UNITS MET
    PARAM TEMP=153.35 <C> PRES=5.

BLOCK FE-102 FLASH2
```

```
    IN-UNITS MET
    PARAM PRES=4.

BLOCK FE-103 FLASH2
    IN-UNITS MET
    PARAM TEMP=137. <C> PRES=3.

BLOCK FE-104 FLASH2
    IN-UNITS MET
    PARAM TEMP=128. <C> PRES=2.

BLOCK FE-105 FLASH2
    IN-UNITS MET
    PARAM TEMP=120. <C> PRES=1.

BLOCK D-101 RADFRAC
    IN-UNITS MET
    PARAM NSTAGE=35 MAXOL=200
    COL-CONFIG CONDENSER=PARTIAL-V
    FEEDS SR-142A 35 ON-STAGE / SR-105 15 ON-STAGE
    PRODUCTS SR-111A 1 V / SR-112A 35 L
    P-SPEC 1 1.2
    COL-SPECS D:F=0.1606 DP-STAGE=0.15 <psi> MOLE-RR=5.
    REAC-STAGES 2 34 R-2
    TRAY-SIZE 1 2 34 SIEVE TRAY-SPACE=2. <ft>

BLOCK D-102 RADFRAC
    IN-UNITS MET
    PARAM NSTAGE=35 MAXOL=200
    COL-CONFIG CONDENSER=TOTAL
    FEEDS SD-101 13
    PRODUCTS SR-118 35 L / SR-130 1 L
    P-SPEC 1 1.1
    COL-SPECS D:F=0.9 DP-STAGE=0.15 <psi> MOLE-RR=5.
    TRAY-SIZE 1 2 34 SIEVE TRAY-SPACE=2. <ft>

BLOCK D-103 RADFRAC
    IN-UNITS MET
    PARAM NSTAGE=5 MAXOL=200
    COL-CONFIG CONDENSER=TOTAL
    FEEDS SD-109 3
    PRODUCTS SR-125 5 L / SR-140 1 L
    P-SPEC 1 1.1
    COL-SPECS D:F=0.9455 MOLE-RR=2.
    TRAY-SIZE 1 2 4 BALLAST TRAY-SPACE=2. <ft>
```

```
BLOCK R-101 RSTOIC
    IN-UNITS MET
    PARAM TEMP=140. <C> PRES=5. <bar>
    STOIC 1 MIXED 3HP -1. / ACRYL-01 1. / WATER 1.
    CONV 1 MIXED 3HP 0.3

BLOCK P-105 PUMP
    IN-UNITS MET
    PARAM PRES=5.1 <bar>

BLOCK PD-101 PUMP
    PARAM DELP=0.1 <atm>

BLOCK PD-104 PUMP
    PARAM DELP=0.1 <atm>

BLOCK PD-107 PUMP
    IN-UNITS MET
    PARAM PRES=5.1 <bar>

BLOCK PE-101 PUMP
    IN-UNITS MET
    PARAM PRES=5.1

BLOCK PE-102 PUMP
    IN-UNITS MET
    PARAM PRES=2.9

BLOCK PE-103 PUMP
    IN-UNITS MET
    PARAM PRES=5.1 <bar>

BLOCK PR-101 PUMP
    IN-UNITS MET
    PARAM PRES=5.1 <bar>

EO-CONV-OPTI

CONV-OPTIONS
    PARAM TEAR-VAR=YES
    WEGSTEIN MAXIT=300

STREAM-REPOR MOLEFLOW MASSFLOW MOLEFRAC MASSFRAC

PROPERTY-REP PCES NOPROP-DATA NODFMS NOPARAM-PLUS
```

```
REACTIONS R-2 REAC-DIST
    IN-UNITS MET
    REAC-DATA 2
    STOIC 2 3HP -1. / ACRYL-01 1. / WATER 1.

REACTIONS R-1 GENERAL
    REAC-DATA 1 NAME=MAIN REAC-CLASS=EQUILIBRIUM
    STOIC 1 MIXED 3HP -1. / ACRYL-01 1. / WATER 1.
;
;
;
;
;
```

Distillation Column Results (D-101)

```
BLOCK:  D-101    MODEL: RADFRAC
 -------------------------------
    INLETS   - SR-142A  STAGE  35
               SR-105   STAGE  15
    OUTLETS  - SR-111A  STAGE   1
               SR-112A  STAGE  35
   PROPERTY OPTION SET:   NRTL      RENON (NRTL) / IDEAL GAS

                  ***  MASS AND ENERGY BALANCE  ***
                        IN          OUT       GENERATION   RELATIVE DIFF.
   TOTAL BALANCE
   MOLE(LBMOL/HR)        7104.15       7582.14       477.992       0.00000
   MASS(LB/HR   )        483521.       483521.                  -0.532814E-12
   ENTHALPY(BTU/HR  )   -0.113317E+10 -0.110503E+10             -0.248296E-01

                  ***  CO2 EQUIVALENT SUMMARY ***
    FEED STREAMS CO2E             2.20888      LB/HR
    PRODUCT STREAMS CO2E          2.20888      LB/HR
    NET STREAMS CO2E PRODUCTION   0.00000      LB/HR
    UTILITIES CO2E PRODUCTION     0.00000      LB/HR
    TOTAL CO2E PRODUCTION         0.00000      LB/HR



                    **********************
                    ****  INPUT DATA  ****
                    **********************

   ****   INPUT PARAMETERS   ****

    NUMBER OF STAGES                              35
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ALGORITHM OPTION                              STANDARD
INITIALIZATION OPTION                         STANDARD
HYDRAULIC PARAMETER CALCULATIONS              NO
INSIDE LOOP CONVERGENCE METHOD                NEWTON
DESIGN SPECIFICATION METHOD                   NESTED
MAXIMUM NO. OF OUTSIDE LOOP ITERATIONS        200
MAXIMUM NO. OF INSIDE LOOP ITERATIONS         10
MAXIMUM NUMBER OF FLASH ITERATIONS            30
FLASH TOLERANCE                               0.000100000
OUTSIDE LOOP CONVERGENCE TOLERANCE            0.000100000

****   COL-SPECS   ****

MOLAR VAPOR DIST / TOTAL DIST                 1.00000
MOLAR REFLUX RATIO                            5.00000
DISTILLATE TO FEED RATIO                      0.16060

**** REAC-STAGES SPECIFICATIONS ****

STAGE  TO  STAGE        REACTIONS/CHEMISTRY ID
  2        34                R-2


    *****  REACTION PARAGRAPH R-2     *****


     ****  REACTION PARAMETERS  ****

RXN NO. TYPE        PHASE     CONC.    TEMP APP TO EQUIL    CONVERSION
                          BASIS          F
  2    EQUILIBRIUM  LIQUID     MOLE-GAMMA      0.0000

    **  STOICHIOMETRIC COEFFICIENTS  **

RXN NO.    WATER       ACRYL-01     3HP        H3PO4       CO2
  2      1.000        1.000       -1.000       0.000       0.000

****    PROFILES   ****

P-SPEC         STAGE   1  PRES, PSIA                17.6351

                 ******************
                 ****  RESULTS  ****
                 ******************
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*** COMPONENT SPLIT FRACTIONS ***

	OUTLET STREAMS	
	SR-111A	SR-112A
COMPONENT:		
WATER	.95672	.43278E-01
ACRYL-01	.26469E-02	.99735
3HP	.80691E-05	.99999
H3PO4	0.0000	1.0000
CO2	.99805	.19462E-02

*** SUMMARY OF KEY RESULTS ***

TOP STAGE TEMPERATURE	F	221.402
BOTTOM STAGE TEMPERATURE	F	310.529
TOP STAGE LIQUID FLOW	LBMOL/HR	5,704.63
BOTTOM STAGE LIQUID FLOW	LBMOL/HR	6,441.21
TOP STAGE VAPOR FLOW	LBMOL/HR	1,140.93
BOILUP VAPOR FLOW	LBMOL/HR	10,062.9
MOLAR REFLUX RATIO		5.00000
MOLAR BOILUP RATIO		1.56227
CONDENSER DUTY (W/O SUBCOOL)	BTU/HR	-0.988931+08
REBOILER DUTY	BTU/HR	0.127029+09

**** MAXIMUM FINAL RELATIVE ERRORS ****

BUBBLE POINT	0.21866E-05	STAGE= 31
COMPONENT MASS BALANCE	0.16052E-08	STAGE= 33 COMP=WATER
ENERGY BALANCE	0.27669E-05	STAGE= 1

**** PROFILES ****

NOTE REPORTED VALUES FOR STAGE LIQUID AND VAPOR RATES ARE THE FLOWS
FROM THE STAGE INCLUDING ANY SIDE PRODUCT.

STAGE	TEMPERATURE F	PRESSURE PSIA	ENTHALPY BTU/LBMOL LIQUID	VAPOR	HEAT DUTY BTU/HR
1	221.40	17.635	-0.12076E+06	-0.10338E+06	-.98893+08
2	221.86	17.785	-0.12082E+06	-0.10342E+06	
14	230.12	19.585	-0.12835E+06	-0.10631E+06	

15	244.34	19.735	-0.14031E+06	-0.11061E+06	
16	244.75	19.885	-0.14030E+06	-0.11061E+06	
33	292.01	22.435	-0.15035E+06	-0.12746E+06	
34	304.74	22.585	-0.15186E+06	-0.13484E+06	
35	310.53	22.735	-0.15325E+06	-0.13836E+06	.12703+09

STAGE	FLOW RATE LBMOL/HR		FEED RATE LBMOL/HR			PRODUCT RATE LBMOL/HR	
	LIQUID	VAPOR	LIQUID	VAPOR	MIXED	LIQUID	VAPOR
1	5705.	1141.			1140.9258		
2	5708.	6846.					
14	6083.	7037.					
15	0.1360E+05	7231.	7104.0961				
16	0.1360E+05	7175.					
33	0.1587E+05	8518.					
34	0.1650E+05	9438.					
35	6441.	0.1006E+05		.50094-01	6441.2124		

**** MASS FLOW PROFILES ****

STAGE	FLOW RATE LB/HR		FEED RATE LB/HR			PRODUCT RATE LB/HR	
	LIQUID	VAPOR	LIQUID	VAPOR	MIXED	LIQUID	VAPOR
1	0.1078E+06	0.2147E+05			.21468+05		
2	0.1083E+06	0.1292E+06					
14	0.1892E+06	0.1616E+06					
15	0.6712E+06	0.2107E+06	.48352+06				
16	0.6714E+06	0.2091E+06					
33	0.1072E+07	0.4581E+06					
34	0.1165E+07	0.6100E+06					
35	0.4621E+06	0.7026E+06		2.2046	.46205+06		

**** MOLE-X-PROFILE ****

STAGE	WATER	ACRYL-01	3HP	H3PO4	CO2
1	0.98382	0.16180E-01	0.14556E-05	0.10000E-29	0.20527E-06
2	0.98228	0.17612E-01	0.11058E-03	0.10000E-29	0.35374E-07
14	0.75810	0.24074	0.11620E-02	0.20542E-27	0.49597E-07
15	0.42131	0.57538	0.16556E-02	0.16544E-02	0.37994E-07
16	0.42143	0.57526	0.16526E-02	0.16537E-02	0.38554E-07
33	0.84686E-01	0.91346	0.43903E-03	0.14169E-02	0.20869E-07
34	0.28366E-01	0.97012	0.14703E-03	0.13629E-02	0.16870E-07
35	0.78937E-02	0.98826	0.35209E-03	0.34920E-02	0.15165E-07

**** MOLE-Y-PROFILE ****

STAGE	WATER	ACRYL-01	3HP	H3PO4	CO2
1	0.98515	0.14807E-01	0.16039E-07	0.99996E-55	0.43906E-04

2	0.98404	0.15951E-01	0.12156E-05	0.10001E-54	0.74886E-05
14	0.90832	0.91662E-01	0.65528E-05	0.20999E-52	0.71565E-05
15	0.79416	0.20583	0.11338E-04	0.17281E-27	0.69695E-05
16	0.79408	0.20590	0.11384E-04	0.17272E-27	0.70402E-05
33	0.33831	0.66168	0.11682E-04	0.13259E-27	0.59178E-05
34	0.13754	0.86244	0.56296E-05	0.13165E-27	0.53324E-05
35	0.41471E-01	0.95851	0.15774E-04	0.34644E-27	0.49960E-05

**** K-VALUES ****

STAGE	WATER	ACRYL-01	3HP	H3PO4	CO2
1	1.0014	0.91512	0.11019E-01	0.11419E-78	213.89
2	1.0018	0.90564	0.10993E-01	0.11260E-78	211.69
14	1.1982	0.38075	0.56393E-02	0.71933E-79	144.29
15	1.8849	0.35772	0.68481E-02	0.82075E-79	183.44
16	1.8842	0.35792	0.68885E-02	0.81455E-79	182.61
33	3.9948	0.72436	0.26608E-01	0.90986E-79	283.57
34	4.8489	0.88900	0.38288E-01	0.93453E-79	316.09
35	5.2537	0.96989	0.44802E-01	0.93931E-79	329.45

**** RATES OF GENERATION ****

LBMOL/HR

STAGE	WATER	ACRYL-01	3HP	H3PO4	CO2
1	0.000	0.000	0.000	0.000	0.000
2	-.6222	-.6222	0.6222	0.000	0.000
14	-3.599	-3.599	3.599	0.000	0.000
15	464.8	464.8	-464.8	0.000	0.000
16	0.3200E-01	0.3200E-01	-.3200E-01	0.000	0.000
33	7.462	7.462	-7.462	0.000	0.000
34	4.648	4.648	-4.648	0.000	0.000
35	0.000	0.000	0.000	0.000	0.000

**** MASS-X-PROFILE ****

STAGE	WATER	ACRYL-01	3HP	H3PO4	CO2
1	0.93827	0.61725E-01	0.69410E-05	0.51877E-29	0.47823E-06
2	0.93259	0.66887E-01	0.52496E-03	0.51644E-29	0.82045E-07
14	0.43899	0.55765	0.33645E-02	0.64704E-27	0.70160E-07
15	0.15375	0.83994	0.30211E-02	0.32842E-02	0.33872E-07
16	0.15382	0.83988	0.30160E-02	0.32832E-02	0.34376E-07
33	0.22592E-01	0.97477	0.58562E-03	0.20561E-02	0.13600E-07
34	0.72416E-02	0.99068	0.18768E-03	0.18926E-02	0.10521E-07
35	0.19824E-02	0.99281	0.44213E-03	0.47704E-02	0.93038E-08

**** MASS-Y-PROFILE ****

STAGE	WATER	ACRYL-01	3HP	H3PO4	CO2
1	0.94319	0.56708E-01	0.76784E-07	0.52077E-54	0.10269E-03
2	0.93909	0.60891E-01	0.58007E-05	0.51916E-54	0.17458E-04

14	0.71239	0.28757	0.25697E-04	0.89587E-52	0.13711E-04
15	0.49096	0.50900	0.35047E-04	0.58111E-27	0.10526E-04
16	0.49085	0.50911	0.35185E-04	0.58075E-27	0.10631E-04
33	0.11333	0.88665	0.19567E-04	0.24160E-27	0.48428E-05
34	0.38340E-01	0.96165	0.78464E-05	0.19962E-27	0.36311E-05
35	0.10700E-01	0.98928	0.20350E-04	0.48622E-27	0.31491E-05

****
***** HYDRAULIC PARAMETERS *****
****

*** DEFINITIONS ***

MARANGONI INDEX = SIGMA - SIGMATO
FLOW PARAM = (ML/MV)*SQRT(RHOV/RHOL)
QR = QV*SQRT(RHOV/(RHOL-RHOV))
F FACTOR = QV*SQRT(RHOV)
WHERE:
SIGMA IS THE SURFACE TENSION OF LIQUID FROM THE STAGE
SIGMATO IS THE SURFACE TENSION OF LIQUID TO THE STAGE
ML IS THE MASS FLOW OF LIQUID FROM THE STAGE
MV IS THE MASS FLOW OF VAPOR TO THE STAGE
RHOL IS THE MASS DENSITY OF LIQUID FROM THE STAGE
RHOV IS THE MASS DENSITY OF VAPOR TO THE STAGE
QV IS THE VOLUMETRIC FLOW RATE OF VAPOR TO THE STAGE

	TEMPERATURE F	
STAGE	LIQUID FROM	VAPOR TO
1	221.40	221.86
2	221.86	222.30
14	230.12	244.34
15	244.34	244.75
16	244.75	245.16
33	292.01	304.74
34	304.74	310.53
35	310.53	212.00

MASS FLOW LB/HR	VOLUME FLOW CUFT/HR	MOLECULAR WEIGHT

STAGE	LIQUID FROM	VAPOR TO	LIQUID FROM	VAPOR TO	LIQUID FROM	VAPOR TO
1	0.10776E+06	0.12923E+06	1891.5	0.28151E+07	18.890	18.878
2	0.10832E+06	0.12979E+06	1901.7	0.27951E+07	18.975	18.947
14	0.18924E+06	0.21071E+06	3306.1	0.27681E+07	31.111	29.141
15	0.67116E+06	0.20911E+06	11636.	0.27276E+07	49.365	29.145
16	0.67135E+06	0.20930E+06	11643.	0.27108E+07	49.358	29.149
33	0.10720E+07	0.60998E+06	19075.	0.34280E+07	67.531	64.629
34	0.11647E+07	0.70261E+06	20912.	0.36583E+07	70.568	69.822
35	0.46205E+06	2.2046	8335.8	15.882	71.734	44.010

	DENSITY LB/CUFT		VISCOSITY CP		SURFACE TENSION DYNE/CM
STAGE	LIQUID FROM	VAPOR TO	LIQUID FROM	VAPOR TO	LIQUID FROM
1	56.971	0.45906E-01	0.26586	0.12800E-01	56.624
2	56.958	0.46432E-01	0.26536	0.12810E-01	56.518
14	57.240	0.76121E-01	0.27549	0.13102E-01	47.264
15	57.679	0.76666E-01	0.29159	0.13110E-01	33.623
16	57.661	0.77210E-01	0.29097	0.13118E-01	33.595
33	56.200	0.17794	0.26625	0.11994E-01	18.400
34	55.693	0.19206	0.25843	0.11746E-01	15.767
35	55.430	0.13881	0.25630	0.18424E-01	14.854

STAGE	MARANGONI INDEX DYNE/CM	FLOW PARAM	QR CUFT/HR	REDUCED F-FACTOR (LB-CUFT)**.5/HR
1		0.23670E-01	79942.	0.60315E+06
2	-.10559	0.23829E-01	79839.	0.60230E+06
14	-5.3227	0.32752E-01	0.10101E+06	0.76372E+06
15	1.7558	0.11702	99507.	0.75522E+06
16	-.27801E-01	0.11737	99264.	0.75325E+06
33	-4.9942	0.98891E-01	0.19320E+06	0.14460E+07
34	-2.6322	0.97342E-01	0.21520E+06	0.16032E+07
35	-.91352	10488.	0.79577	5.9172

****
***** TRAY SIZING CALCULATIONS *****
****

****
*** SECTION 1 ***

****

STARTING STAGE NUMBER		2
ENDING STAGE NUMBER		34
FLOODING CALCULATION METHOD		GLITSCH

DESIGN PARAMETERS

PEAK CAPACITY FACTOR		1.00000
SYSTEM FOAMING FACTOR		1.00000
FLOODING FACTOR		0.80000
MINIMUM COLUMN DIAMETER	FT	1.00000
MINIMUM DC AREA/COLUMN AREA		0.100000
HOLE AREA/ACTIVE AREA		0.12000

TRAY SPECIFICATIONS

TRAY TYPE		SIEVE
NUMBER OF PASSES		1
TRAY SPACING	FT	2.00000

***** SIZING RESULTS @ STAGE WITH MAXIMUM DIAMETER *****

STAGE WITH MAXIMUM DIAMETER		34
COLUMN DIAMETER	FT	20.1889
DC AREA/COLUMN AREA		0.100000
DOWNCOMER VELOCITY	FT/SEC	0.18146
FLOW PATH LENGTH	FT	13.8708
SIDE DOWNCOMER WIDTH	FT	3.15907
SIDE WEIR LENGTH	FT	14.6695
CENTER DOWNCOMER WIDTH	FT	0.0
CENTER WEIR LENGTH	FT	0.0
OFF-CENTER DOWNCOMER WIDTH	FT	0.0
OFF-CENTER SHORT WEIR LENGTH	FT	0.0
OFF-CENTER LONG WEIR LENGTH	FT	0.0
TRAY CENTER TO OCDC CENTER	FT	0.0

**** SIZING PROFILES ****

STAGE	DIAMETER	TOTAL AREA	ACTIVE AREA	SIDE DC AREA
	FT	SQFT	SQFT	SQFT
2	10.965	94.431	75.545	9.4431
3	10.951	94.189	75.351	9.4189
4	10.938	93.969	75.175	9.3969

5	10.927	93.777	75.021	9.3777
6	10.918	93.624	74.899	9.3624
7	10.912	93.525	74.820	9.3525
8	10.911	93.505	74.804	9.3505
9	10.917	93.606	74.885	9.3606
10	10.935	93.906	75.125	9.3906
11	10.973	94.574	75.659	9.4574
12	11.059	96.047	76.838	9.6047
13	11.277	99.883	79.906	9.9883
14	12.043	113.90	91.122	11.390
15	13.662	146.59	117.27	14.659
16	13.640	146.13	116.90	14.613
17	13.619	145.67	116.54	14.567
18	13.598	145.22	116.17	14.522
19	13.577	144.77	115.82	14.477
20	13.556	144.33	115.46	14.433
21	13.535	143.89	115.11	14.389
22	13.515	143.46	114.77	14.346
23	13.495	143.03	114.43	14.303
24	13.475	142.61	114.09	14.261
25	13.456	142.21	113.76	14.221
26	13.438	141.84	113.47	14.184
27	13.427	141.60	113.28	14.160
28	13.437	141.80	113.44	14.180
29	13.522	143.60	114.88	14.360
30	13.848	150.61	120.49	15.061
31	14.823	172.56	138.05	17.256
32	16.892	224.10	179.28	22.410
33	18.968	282.59	226.07	28.259
34	20.189	320.12	256.10	32.012

Flash Vessel Results (FE-101)

BLOCK: FE-101 MODEL: FLASH2

INLET STREAM: S-E102
OUTLET VAPOR STREAM: S-E103
OUTLET LIQUID STREAM: S-E104
PROPERTY OPTION SET: NRTL RENON (NRTL) / IDEAL GAS

*** MASS AND ENERGY BALANCE ***

	IN	OUT	RELATIVE DIFF.
TOTAL BALANCE			
MOLE(LBMOL/HR)	37429.0	37429.0	-0.194394E-15
MASS(LB/HR)	728180.	728180.	0.383692E-14
ENTHALPY(BTU/HR)	-0.471028E+10	-0.437906E+10	-0.703182E-01

*** CO2 EQUIVALENT SUMMARY ***

FEED STREAMS CO2E 0.00000 LB/HR
PRODUCT STREAMS CO2E 0.00000 LB/HR
NET STREAMS CO2E PRODUCTION 0.00000 LB/HR
UTILITIES CO2E PRODUCTION 0.00000 LB/HR
TOTAL CO2E PRODUCTION 0.00000 LB/HR

*** INPUT DATA ***

TWO PHASE TP FLASH
SPECIFIED TEMPERATURE F 308.030
SPECIFIED PRESSURE PSIA 73.4797
MAXIMUM NO. ITERATIONS 30
CONVERGENCE TOLERANCE 0.000100000

*** RESULTS ***

OUTLET TEMPERATURE F 308.03
OUTLET PRESSURE PSIA 73.480
HEAT DUTY BTU/HR 0.33122E+09
VAPOR FRACTION 0.28541

V-L PHASE EQUILIBRIUM :

COMP	F(I)	X(I)	Y(I)	K(I)
WATER	0.98002	0.97242	0.99905	1.0274
3HP	0.19978E-01	0.27578E-01	0.94915E-03	0.34417E-01

BLOCK: HX-101 MODEL: HEATER

INLET STREAM: S-E103
OUTLET STREAM: S-E113
OUTLET HEAT STREAM: H1
PROPERTY OPTION SET: NRTL RENON (NRTL) / IDEAL GAS

*** MASS AND ENERGY BALANCE ***

	IN	OUT	RELATIVE DIFF.
TOTAL BALANCE			
MOLE(LBMOL/HR)	10682.6	10682.6	0.00000
MASS(LB/HR)	193182.	193182.	0.00000
ENTHALPY(BTU/HR)	-0.109207E+10	-0.109207E+10	0.00000

*** CO2 EQUIVALENT SUMMARY ***

FEED STREAMS CO2E 0.00000 LB/HR
PRODUCT STREAMS CO2E 0.00000 LB/HR
NET STREAMS CO2E PRODUCTION 0.00000 LB/HR

UTILITIES CO2E PRODUCTION 0.00000 LB/HR
TOTAL CO2E PRODUCTION 0.00000 LB/HR

*** INPUT DATA ***
TWO PHASE TP FLASH
SPECIFIED TEMPERATURE F 294.300
SPECIFIED PRESSURE PSIA 72.0101
MAXIMUM NO. ITERATIONS 30
CONVERGENCE TOLERANCE 0.000100000

*** RESULTS ***
OUTLET TEMPERATURE F 294.30
OUTLET PRESSURE PSIA 72.010
HEAT DUTY BTU/HR -0.17798E+09
OUTLET VAPOR FRACTION 0.0000
PRESSURE-DROP CORRELATION PARAMETER 88.110

V-L PHASE EQUILIBRIUM :

COMP	F(I)	X(I)	Y(I)	K(I)
WATER	0.99905	0.99905	0.99997	0.85212
3HP	0.94915E-03	0.94915E-03	0.31969E-04	0.28674E-01

Pump Results (PD-101)

BLOCK: PD-101 MODEL: PUMP

INLET STREAM: SR-112A
OUTLET STREAM: SD-101
PROPERTY OPTION SET: NRTL RENON (NRTL) / IDEAL GAS

*** MASS AND ENERGY BALANCE ***

	IN	OUT	RELATIVE DIFF.
TOTAL BALANCE			
MOLE(LBMOL/HR)	6441.21	6441.21	0.00000
MASS(LB/HR)	462053.	462053.	0.00000
ENTHALPY(BTU/HR)	-0.987085E+09	-0.987083E+09	-0.296945E-05

*** CO2 EQUIVALENT SUMMARY ***
FEED STREAMS CO2E 0.429884E-02 LB/HR
PRODUCT STREAMS CO2E 0.429884E-02 LB/HR
NET STREAMS CO2E PRODUCTION 0.00000 LB/HR
UTILITIES CO2E PRODUCTION 0.00000 LB/HR

TOTAL CO2E PRODUCTION 0.00000 LB/HR

*** INPUT DATA ***

PRESSURE CHANGE PSI 1.46959
DRIVER EFFICIENCY 1.00000

FLASH SPECIFICATIONS:
LIQUID PHASE CALCULATION
NO FLASH PERFORMED
MAXIMUM NUMBER OF ITERATIONS 30
TOLERANCE 0.000100000

*** RESULTS ***

VOLUMETRIC FLOW RATE CUFT/HR 8,335.78
PRESSURE CHANGE PSI 1.46959
NPSH AVAILABLE FT-LBF/LB 0.0
FLUID POWER HP 0.89092
BRAKE POWER HP 1.15197
ELECTRICITY KW 0.85902
PUMP EFFICIENCY USED 0.77339
NET WORK REQUIRED HP 1.15197
HEAD DEVELOPED FT-LBF/LB 3.81781

Reactor Vessel Results (R-101)

BLOCK: R-101 MODEL: RSTOIC

INLET STREAMS: SR-104 SR-101 SR-133
INLET HEAT STREAM: RXHT
OUTLET STREAM: SR-105
OUTLET HEAT STREAM: 2
PROPERTY OPTION SET: NRTL RENON (NRTL) / IDEAL GAS

*** MASS AND ENERGY BALANCE ***

	IN	OUT	GENERATION	RELATIVE DIFF.
TOTAL BALANCE				
MOLE(LBMOL/HR)	6898.57	7104.10	205.827	0.417424E-04
MASS(LB/HR)	483543.	483519.		0.502648E-04
ENTHALPY(BTU/HR)	-0.113542E+10	-0.113538E+10		-0.386212E-04

*** CO2 EQUIVALENT SUMMARY ***

FEED STREAMS CO2E 0.425585E-02 LB/HR
PRODUCT STREAMS CO2E 0.425637E-02 LB/HR
NET STREAMS CO2E PRODUCTION 0.523444E-06 LB/HR
UTILITIES CO2E PRODUCTION 0.00000 LB/HR
TOTAL CO2E PRODUCTION 0.523444E-06 LB/HR

*** INPUT DATA ***

STOICHIOMETRY MATRIX:

REACTION # 1:
SUBSTREAM MIXED :
WATER 1.00 ACRYL-01 1.00 3HP -1.00

REACTION CONVERSION SPECS: NUMBER= 1
REACTION # 1:
SUBSTREAM:MIXED KEY COMP:3HP CONV FRAC: 0.3000

TWO PHASE TP FLASH	
SPECIFIED TEMPERATURE F	284.000
SPECIFIED PRESSURE PSIA	72.5189
MAXIMUM NO. ITERATIONS	30
CONVERGENCE TOLERANCE	0.000100000
SIMULTANEOUS REACTIONS	
GENERATE COMBUSTION REACTIONS FOR FEED SPECIES	NO

*** RESULTS ***

OUTLET TEMPERATURE	F	284.00
OUTLET PRESSURE	PSIA	72.519
HEAT DUTY	BTU/HR	0.23267E+07
NET DUTY	BTU/HR	0.22153E+07
VAPOR FRACTION		0.0000

REACTION EXTENTS:

REACTION NUMBER	REACTION EXTENT LBMOL/HR
1	205.83

V-L PHASE EQUILIBRIUM :

COMP	F(I)	X(I)	Y(I)	K(I)
WATER	0.98078E-01	0.98078E-01	0.39178	1.0707
ACRYL-01	0.83116	0.83116	0.60655	0.19561
3HP	0.67601E-01	0.67601E-01	0.16646E-02	0.66002E-02
H3PO4	0.31661E-02	0.31661E-02	0.33169E-81	0.28082E-79

CO_2	0.13612E-07	0.13612E-07	0.42155E-05	83.014

Aspen IPE Summary

Aspen IPE was used for all most equipment costing and sizing. Formatted sample output from IPE is show in Table 34 and Table 35.

Aspen IPE Costing Output						
Name	Group	Type	Equipment Cost [USD]	Total Direct Cost [USD]	Equipment Weight [LBS]	Total Installed Weight [LBS]
D-101-bottoms split		C	0	0	0	0
D-101-cond		DHE FIXED T S	82900	204000	35700	65338
D-101-cond acc		DHT HORIZ DRUM	19000	116100	4000	16676
D-101-overhead split		C	0	0	0	0
D-101-reb		DRB U TUBE	1.21E+06	1.52E+06	457900	539318
D-101-reflux pump		DCP CENTRIF	7100	45900	660	6756
D-101-tower		DTW TRAYED	1.10E+06	1.92E+06	486300	683815
D-102-bottoms split		C	0	0	0	0
D-102-cond		DHE FIXED T S	242000	411900	103200	145878
D-102-cond acc		DHT HORIZ DRUM	65200	282900	29300	78048
D-102-overhead split		C	0	0	0	0
D-102-reflux pump		DCP CENTRIF	95900	264700	5000	46603
D-102-tower		DTW TRAYED	2.82E+06	5.63E+06	1.64E+06	2.22E+06
D-103-bottoms split		C	0	0	0	0
D-103-cond		DHE FIXED T S	21000	88000	6200	18894
D-103-cond acc		DHT HORIZ DRUM	20600	128100	4800	21634
D-103-overhead split		C	0	0	0	0
D-103-reb		DRB U TUBE	42700	127500	14900	29940
D-103-reflux pump		DCP CENTRIF	7800	47300	710	7039
D-103-tower		DTW TRAYED	87200	312800	20800	63888
F-101-flash vessel		DVT CYLINDER	43700	193000	14700	44487
F-102-flash vessel		DVT CYLINDER	34900	174300	11400	38004
F-103-flash vessel		DVT CYLINDER	30400	164300	7700	32398
F-104-flash vessel		DVT CYLINDER	23000	141300	4900	24455
F-105-flash vessel		DVT CYLINDER	21300	129000	4100	19777
HX-101		DHE FLOAT HEAD	117900	249800	45400	78539
HX-102		DHE FLOAT HEAD	128500	260900	50800	84125
HX-103		DHE FLOAT HEAD	118600	249300	46000	78492
HX-104		DHE FLOAT HEAD	56300	159200	21300	46010
HX-105		DHE FLOAT HEAD	27900	110200	9100	27109
HX-108		DHE FLOAT HEAD	46200	156700	16900	46252
HX-109		DHE FLOAT HEAD	17500	89900	4600	20391
HX-110		DHE FLOAT HEAD	8000	44800	490	3486
M-101		C	0	0	0	0
M-102		C	0	0	0	0
M-103		C	0	0	0	0
PD-101		DCP CENTRIF	11100	68800	830	13169
PD-103		DCP CENTRIF	13800	67500	1100	12055
PD-104		DCP CENTRIF	4700	37400	200	4803
PD-107		DCP CENTRIF	4100	27900	230	2838
PE-101		DCP CENTRIF	16600	78600	1500	14802
PE-102		DCP CENTRIF	8000	54800	680	9149
PE-103		DCP CENTRIF	5500	38200	350	4947
PR-101		DCP CENTRIF	4200	25900	200	2133
R-101		DAT REACTOR	225300	410600	48600	79163
S-101		C	0	0	0	0
S-102		C	0	0	0	0

Table 34. Sample IPE Costing Output

Aspen IPE Pump Sizing Output						
Name	PD-104	PD-107	PE-101	PE-102	PE-103	PR-101
Group						
Item Reference Number	42	43	44	45	46	47
Item description	PD-104	PD-107	PE-101	PE-102	PE-103	PR-101
User tag number	PD-104	PD-107	PE-101	PE-102	PE-103	PR-101
Quoted cost per item [USD]						
Currency unit for matl cost						
Number of identical items						
Casing material						
Liquid flow rate [GPM]	117.17	10.2972	1601.34	501.878	139.838	0.079699
Fluid head [FEET]	3.84912	200.46	139.335	64.8948	125.342	225.326
Speed						
Fluid specific gravity	0.881959	0.666099	0.998927	0.993925	1.09238	0.607658
Driver power [HP]						
Driver type						
Seal type						
Design gauge pressure [PSIG]	35.304	84.2732	85.2533	35.304	84.2732	84.2732
Design temperature [DEG F]	360.729	422.811	250	250	298.42	250
Fluid viscosity [CPOISE]		1.00135	0.704182	0.911465		1.00114
Pump efficiency [PERCENT]	54.3601	29.5658	79.6826	70.4708	56.5897	29.5658

Aspen IPE Pump Sizing Output					
Name	D-101-reflux pump	D-102-reflux pump	D-103-reflux pump	PD-101	PD-103
Group					
Item Reference Number	6	13	20	40	41
Item description	D-101-reflux pump	D-102-reflux pump	D-103-reflux pump	PD-101	PD-103
User tag number	D-101-reflux pump	D-102-reflux pump	D-103-reflux pump	PD-101	PD-103
Quoted cost per item [USD]					
Currency unit for matl cost					
Number of identical items					
Casing material					
Liquid flow rate [GPM]	265.595	6049.84	320.423	1143.19	998.224
Fluid head [FEET]				3.82346	147.68
Speed					
Fluid specific gravity	0.887876	0.90416	0.902658	0.887876	0.90416
Driver power [HP]					
Driver type					
Seal type					
Design gauge pressure [PSIG]	35.304	35.304	35.304	35.304	84.2732
Design temperature [DEG F]	271.402	339.407	341.714	360.546	340.153
Fluid viscosity [CPOISE]					
Pump efficiency [PERCENT]	70	70	70	77.3394	76.3198

Table 35. Sample IPE Sizing Output

Appendix III - Batch Process Scheduling

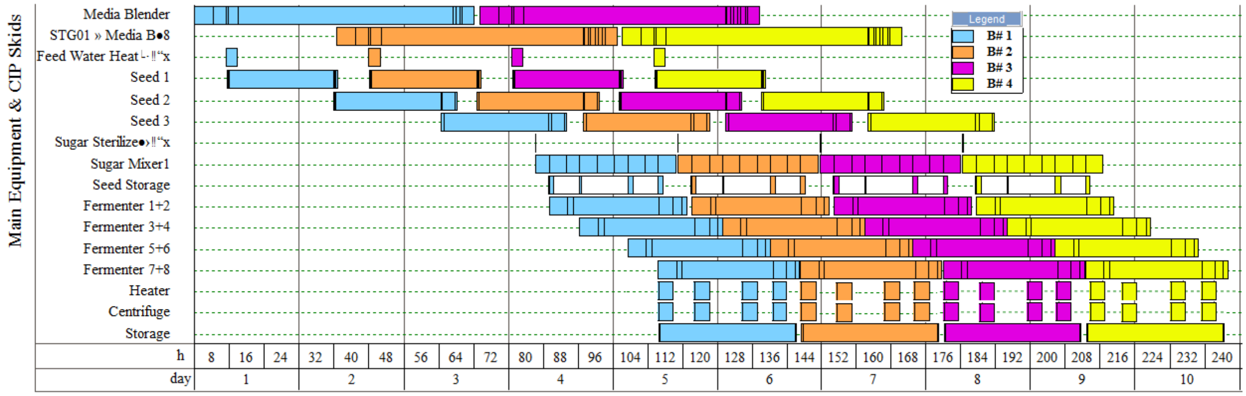


Figure 12. Gantt Chart – Fermentation Process

Media Blender (MF-101)

The media blender mixer (MF-101) mixes the media and water flow streams. Flow in is for 4 hours. The mixture is agitated 3 hours. Then .38 gal are sent to FF-101. After 24 hours, 76.1 gal are sent to FF-102, and then after another 24 hours, 15,200 gal are sent to FF-103. Twenty hours after this 760,000 gal are sent to the glucose mixture over the course of 4 hours. This is repeated every 6 hours for fermenters FF-106 to FF-111.

Feed Water Heater (HXF-101)

The Feed Water Heater (HXF-101) sterilizes the media and water stream as it exits MF-101 by heating the flow streams to 120^{o}F for one hour.

Seed Fermenter 1 (FF-101)

FF-101 has media flow in for .25 hours. Fermentation then takes 24 hours. Material then flows out for .25 hours. CIP and SIP cleaning are done each batch for .5 hours and .25 hours respectively.

Seed Fermenter 2 (FF-102)

Media and cells flow into SF-102 for .25 hours. Fermentation takes 24 hours. Material then flows out for .25 hours. CIP and SIP cleaning are done each batch for .5 hours and .25 hours respectively.

Seed Fermenter3(FF-103)

Media and cells flow into SF-103 for .25 hours. Fermentation takes 24 hours. Material then flows out for .5 hours. CIP and SIP cleaning are done each batch for 1 and .5 hours respectively.

Sugar Sterilizer (HXF-102)

HXF-102 sterilizes the incoming glucose stream by heating it for 5 minutes to 120^{o}F. This is only done for five minutes because longer times would cause the glucose to caramelize.

Sugar Mixer (MF-102)

MF-102 mixes the glucose and water/media streams. It is sized to mix enough media for two of the large fermenters (760,000gal). Flow time of material into the fermenter is 4 hours. The ingredients are then mixed for 2 hours and then pumped to the large fermenters over the next 4 hours. This repeats four times per batch.

Seed Storage (ST-101)

ST-101 stores material from SF-101 until a portion is discharged to the large fermenters. The flow in takes .5 hours. Flow out occurs every 6 hours and takes 1 hour to complete.

Fermenters 1-8 (FF-104 to FF-111)

These fermenters are the bottleneck units for this process. Media containing glucose comes in over the course of 4 hours. Fermentation then occurs for 23 hours. Flow of material out takes 3 hours. CIP and SIP are done each batch for 2 and 1 hour, respectively. The flows in and out of the fermenter are staggered so that FF-104 and FF-105, operate 6 hours ahead of FF-106 and 107, 12 hours ahead of FF-108 and 109, and 18 hours ahead of FF-110 and 111. This is done to reduce the size of mixers, pumps, and heat exchangers necessary for the process.

Heater (HXF-114)

HXF-114 heats the fermenter exit flow to 120^{o}F. This occurs during each of the 3 hours long out flows from the fermenters (for a total of 12 hours per batch)

Centrifuge (CF-101)

CF-101 centrifuges each fermenter exit flow stream for 3 hours each.

Storage (ST-102)

Material is stored in ST-102 for 3 hours every 6 hours. SE-101 is drained from ST-102 continuously to enter the dehydration reaction process.

Appendix IV - Design Calculations

Heat Exchanger Sizing

The following is a sample calculation for sizing HXF-102. All heat exchangers were sized with the following manner.

The flow rate on the tube side is SF-108 which is 139,959 lb/hr glucose, which has a heat capacity of 2.77 BTU/lb^{0}F. The temperature change of the stream was an increase of 18˚F. We then calculated the heat duty with the equation below:

$$Q = \dot{m}C_p\Delta T$$

The heat duty of the stream was therefore 6,975,457 BTU/hr.

The heat transfer coefficient is estimated from *Seider, Seader, Lewin, Widagdo,* Table 18.5. For this heat exchanger a heat transfer coefficient of 250 BTU/hr*sqft*˚F was used. For all other heat exchangers, this value varies based on the state and properties of the streams involved. Table 18.5 details the applicable heat transfer coefficients and the average value of the range suggested was used throughout the report.

To calculate heat transfer area, the following equation was used:

$$Q = UA\Delta T_{lm}$$

$$\Delta T_{lm} = \frac{\left[\left(T_{h,i} - T_{c,o}\right) - \left(T_{h,o} - T_{c,i}\right)\right]}{\ln\left(\frac{\left(T_{h,i} - T_{c,o}\right)}{\left(T_{h,o} - T_{c,i}\right)}\right)}$$

Area was calculated to be 54,400 ft^2.

To calculate the shell-side steam utility requirements, the calculated heat duty was divided by the heat capacity of steam at 50 psi (926 BTU/lb˚F) to determine a steam flow rate of 7,533 lb/hr.

Distillation Column Sizing and Tray Efficiency

The number of theoretical stages as reported by Aspen was 24.5 . Assuming a 70% tray efficiency as suggested by *Seider, Seader, Lewin, Widagdo,* pg. 503 for distillation columns, the number of actual stages was 35 stages. To determine the diameter, Aspen IPE was used. To determine the height the following equation was used:

L= (N-2)stages* spacing (ft) + 14 ft

Two stages were subtracted to account for the reboiler and condenser.

To determine shell thickness of all pressure vessels and distillation columns, the following equation was used:

$$t_p = \frac{P_d D_i}{2SE - 1.2P_d}$$

Where t_p = wall thickness in inches to withstand the internal pressure, P_d = internal design gauge pressure in psig, and D_i = inside shell diameter in inches, S = maximum allowable stress of the shell material at the design temperature in pound per square inch, and E=fractional weld efficiency (assumed at 85% per *Seider, Seader, Lewin and Widagdo*).

To calculate reflux ratio while minimizing the operating and capital cost, *Geankopolis* suggests that the reflux ratio for a column be set between $R=1.2R_{min}$ to$1.5R_{min}$.We used $1.4R_{min}$ to calculate the actual reflux ratio used in the distillation columns, with Aspen used to estimate the minimum reflux ratio.

Reflux Pumps and Pump Calculations

The utility requirement for pumps was calculated with the following equation, all reported in Aspen or specified by process requirements:

$$\dot{W} = Fv(\Delta P)$$

Where F is the molar flow rate, v is the molar volume, and P is pressure.

To calculated the pump head for the pumps:

$$H, pump\ head = \left(\frac{V_d^2}{2g} + z_d + \frac{P_d}{\rho_d g}\right) - \left(\frac{V_s^2}{2g} + z_s + \frac{P_s}{\rho_s g}\right)$$

Where *V* is the average velocity of the liquid, *z* is the elevation, P is the pressure of the liquid, g is the gravitational acceleration, and ρ is the liquid density.

For the reflux pumps, since the liquid needed to be pumped to the top tray of the distillation tower, we wanted to insure a flow worthy driving force, so we added 15 additional ft to the height of the respective distillation tower in our calculations. This result was used as our pump head.

Electricity requirements and brake power were taken from the model summary reports in Aspen.

Reflux Accumulators and Reactor Vessel

Reflux accumulators and the reactor vessel were designed with a mean residence time of 10 minutes and sizing calculations were done with Aspen IPE.

Centrifuge

Professor Leonard Fabiano suggested we use 0.9 hp per 1000 lb/hr flow to calculate the power requirements for the centrifuge.

Mixers and Storage Tanks

The following is a sample calculation for sizing MF-101. All storage tanks and mixers were sized with the following manner.

$$\boldsymbol{Volume\ (gallons) = flow\ rate\ in\ \left(\frac{gal}{min}\right) * \left(\frac{60min}{hr}\right) * total\ flow\ time\ per\ batch\ (hr) * volume\ capacity}$$

The total flow rate of the streams flowing into the mixer is 2,905.2 gpm. The total flow time of these streams is 4 hours. By assuming a volume capacity if 77% and substituting these numbers in the equation, the resulting volume of MF-101 volume is 535,488 gallons.

In order to calculate the power requirements for the impellers used in the mixers, a factor of 1 hp per 1,000 gallons was used.

Fermenter Sizing

The fermenters for the process were sized according to the studied yield and sized to give the appropriate amount of overall product. For process fermenters this was calculated according to the following method:

$$\frac{Product\left[\frac{kg}{yr}\right]}{365.25\frac{days}{yr} * Uptime * 24\frac{hrs}{day}} * \frac{Batch\ Time\left[\frac{hours}{batch}\right]}{Separations\ Yield} = Required\ 3HP\ \left[\frac{kg}{batch}\right]$$

$$Total\ Volume\ \left[\frac{m^3}{batch}\right] = \frac{Required\left[\frac{kg}{batch}\right]}{Final\ 3HP\ \%\ \left[3HP\frac{kg}{kg}\right]} * Fermentation\ Density\ \left[\frac{kg}{m^3}\right]$$

The batch time for the process was calculated by simulation in SuperPro Designer and for the proposed process was calculated to be 31 hours. Uptime for the process was assumed to be 85%, based on the suggestion of Mr. Stephen Tieri. This results in 7446 hours of uptime per year.

According to the design specification, the total product is 160,000,000 kg/yr and the overall separations and conversion yield was 89.9%. The final mass percent of 3-HP in the fermentation broth was calculated to be 9.25%, based on an assumed 1.85 mol 3-HP / mol glucose conversion in fermentation and an initial 10% by mass glucose medium. The 10% by mass solution was the result of a small scale laboratory measurement of *E. coli* growth rates in varying glucose concentration solutions. The 10% solution was found to have maximum growth rate, without any measurable glucose inhibition which began to occur at higher glucose concentrations.

The sizing of the process and seed fermenters was calculated using 89% capacity of fermentation, meaning that the total volume calculated above was divided by 89% to get the total capacity of the process fermenters. The number of actual fermenters was then calculated to give an economically feasible size of fermenters (around 500,000 gallons each). This results in 8 total process fermenters which were staggered in the process scheduling to produce a pseudo-continuous batch process. Because the fermenters are airlift agitated, the aspect ratio (Length / Diameter) is set at 2, based on suggestions from Dr. Joye Bramble.

The seed fermenters for the process were sized based on similar operating conditions but with a 200x step down in required volume in each stage. The 200x dilution per step up in fermentation was taken from US Patent 7,186,541 and it was assumed that the starting volume was 1.5 mL of *E. coli* inoculums, with a 200x step up in total volume for each seed fermenter, for a total of 3 step up seed fermenters before the process fermentation steps.

Aspen IPE (Purchase and Bare Modules Costs)

Aspen IPE was used to calculate all process unit purchase and bare module costs at an assumed CE index of 652.43 based on 2012 costs. For those process units designed in SuperPro Designer, Aspen Economic Analyzer was used to enter required equipment specifications and obtain purchase costs, with an assumed bare module factor of 3.21 (based on suggestions by *Seider, Seader, Lewin and Widagdo*). A sample Aspen IPE output is shown in the Aspen IPE Summary section of the report on page 226.

CE Index Adjustments

Due to general inflation in chemical engineering process equipment, the costs estimated by Aspen IPE were adjusted by the CE index increase factor to the estimated 2013 value. The 2013 value was estimated by linear regression the natural log of the historical CE index values as a function of year. Specifically, historical data resulted in the following regression equation:[29]

$$\ln(CE\ Index) = .0187 * Year - 31.28$$

As seen in this regression, an extra year of inflation corresponds to an increase factor of:

$$\frac{CE_{i+1}}{CE_i} = \exp(.0187) = 1.0188$$

Thus, a factor of 1.0188 was applied to the bare module costs estimates from Aspen IPE to correct for the estimated 2013 beginning of construction.

Utility Requirements

The proposed process uses 5 different types of assumed utilities: Low and High Pressure Steam, Cooling Water, Electricity and Waste Water Treatment. The methods used to estimate and price these utility requirements are shown on the following page.

[29] [9] CEPCI

Steam Requirements – steam is used to heat streams throughout the proposed process and the amount and type of steam depends on the total heat duty required and temperature of the heated stream. Steam is produced at pressure to vary the saturation temperature, changing the temperature at which condensation occurs. 50 psig steam (low pressure) has a saturation temperature of 297.7˚F, while 150 psig steam has a saturation temperature of 365.9˚F. In the proposed process, low pressure steam is used for sterilization purposes, while high pressure steam is used for reboilers and separation procedures. In all cases the heat duty is calculated according to the following equation:

$$Q = \dot{m} C_p \Delta T$$

Where m is the mass flow rate of the heated stream, C_p is the specific heat capacity of the stream and ΔT is the required temperature increase of the heated stream. Once this heat duty is calculated, the amount of steam can be calculated by using the pressure dependent enthalpy of evaporation for steam (BTU/lb) according to the following equation:

$$Q = \Delta H_{vap} \dot{m}$$

Where m is the required mass flow rate of steam and ΔH_{vap} is the enthalpy of evaporation for steam at the specified pressure.

Electricity Requirements – Various process units require electrical power input, with pumps being the most common. The electricity requirements of each process were estimated by Aspen IPE, heuristics formulas provided by *Seider et. Al,* or by suggestion of Mr. Leonard Fabiano

NPV Calculations

Net Present Value is calculated using the free cash flow for a project or proposed process, and assumes a discount rate commiserate with the relative risk of the expected cash flows and returns available from the project. Cash flow is calculated in each period according to the following equation:

$$CF = Net\ Income + Depreciation + \Delta Working\ Capital - Capital\ Investment$$

In this formula, Net Income is the typical accounting definition, but is shown in the following equation:

$$Net\ Income = (Revenue - Fixed\ Costs - Variable\ Costs - Depreciation) * (1 - Tax)$$

Where revenue is calculated as price multiplied by quantity of output, while fixed and variable costs depend directly on economic and operating assumptions of the process, which are summarized in the economic and operating costs section of the report.

NPV is calculated over the life of the project according to this equation:

$$NPV = \sum_{i=0}^{T} \frac{CF_i}{(1+r)^i}, \qquad where\ T = life\ of\ the\ project, r = discount\ rate, and$$

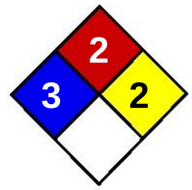
$$CF_i\ is\ the\ free\ cash\ flow\ in\ year\ i$$

This calculation was automated via Microsoft Excel ® and used to produce various sensitivities and make decisions regarding various design decisions. It is worth noting that NPV is the economic profitability criterion which maximizes value for the company and is therefore the criterion used to make the majority of design economic decisions. However, NPV is dependent on the scale of the project and variations in scale of the project make it difficult to compare NPV amongst cases. Since the assumed goal of the company is maximized value, the maximum NPV project should always be selected, absent financing constraint. However, given financing constraints, such as loan or leverage limits, the maximum NPV project may not be available in terms of initial investment. To make a full recommendation on the project profitability, financial constraints or other operating conditions would need to be known and may or may not correspond with that project case which maximizes NPV.

IRR Calculations

The Internal Rate of Return (IRR) is defined as that discount rate which produces a zero NPV for a series of cash flows. It gives a scale independent measure of project economic profitability and can be thought of as the compounded return available from an investment in the project. Mathematical issues with IRR exist however, and in general, it is the solution to an n^{th} degree polynomial, where n is the number of periods in the project life. Because of this, there is not in general a unique solution and a single real solution only exists when there is an initial negative investment and strictly positive cash flows thereafter. In general the number of real solutions is equal to the number of sign changes in the cash flow series. Because of this mathematical misbehavior, IRR cannot be used as a profitability criterion absent critical analysis on other economic criterion for the project.

Appendix V - Material Safety Data Sheets



Health	3
Fire	2
Reactivity	2
Personal Protection	

Material Safety Data Sheet
Acrylic Acid MSDS

Section 1: Chemical Product and Company Identification

Product Name: Acrylic Acid

Catalog Codes: SLA3406

CAS#: 79-10-7

RTECS: AS4375000

TSCA: TSCA 8(b) inventory: Acrylic Acid

CI#: Not available.

Synonym: Propenoic Acid Ethylenecarboxylic Acid

Chemical Name: Acrylic Acid

Chemical Formula: C3-H4-O2

Contact Information:

Sciencelab.com, Inc.
14025 Smith Rd.
Houston, Texas 77396

US Sales: **1-800-901-7247**
International Sales: **1-281-441-4400**

Order Online: ScienceLab.com

CHEMTREC (24HR Emergency Telephone), call:
1-800-424-9300

International CHEMTREC, call: 1-703-527-3887

For non-emergency assistance, call: 1-281-441-4400

Section 2: Composition and Information on Ingredients

Composition:

Name	CAS #	% by Weight
Acrylic Acid	79-10-7	100

Toxicological Data on Ingredients: Acrylic Acid: ORAL (LD50): Acute: 33500 mg/kg [Rat]. 2400 mg/kg [Mouse]. DERMAL (LD50): Acute: 294 mg/kg [Rabbit]. VAPOR (LC50): Acute: 5300 mg/m 2 hours [Mouse]. 75 ppm 6 hours [Monkey].

Section 3: Hazards Identification

Potential Acute Health Effects:
Very hazardous in case of skin contact (permeator), of eye contact (irritant, corrosive). Corrosive to skin and eyes on contact. Liquid or spray mist may produce tissue damage particularly on mucous membranes of eyes, mouth and respiratory tract. Skin contact may produce burns. Inhalation of the spray mist may produce severe irritation of respiratory tract, characterized by coughing, choking, or shortness of breath. Severe over-exposure can result in death. Inflammation of the eye is characterized by redness, watering, and itching.

Potential Chronic Health Effects:
CARCINOGENIC EFFECTS: A4 (Not classifiable for human or animal.) by ACGIH, 3 (Not classifiable for human.) by IARC. MUTAGENIC EFFECTS: Classified POSSIBLE for human. Mutagenic for mammalian germ and somatic cells. TERATOGENIC EFFECTS: Classified SUSPECTED for human. DEVELOPMENTAL TOXICITY: Classified Reproductive system/toxin/male [POSSIBLE]. Classified Development toxin [SUSPECTED]. The substance is toxic to bladder, brain, upper respiratory tract, eyes, central nervous system (CNS). Repeated or prolonged exposure to the substance can produce target organs damage. Repeated or prolonged contact with spray mist may produce chronic eye irritation and severe skin irritation.

Repeated or prolonged exposure to spray mist may produce respiratory tract irritation leading to frequent attacks of bronchial infection. Repeated exposure to a highly toxic material may produce general deterioration of health by an accumulation in one or many human organs.

Section 4: First Aid Measures

Eye Contact:
Check for and remove any contact lenses. In case of contact, immediately flush eyes with plenty of water for at least 15 minutes. Cold water may be used. Get medical attention immediately.

Skin Contact:
In case of contact, immediately flush skin with plenty of water for at least 15 minutes while removing contaminated clothing and shoes. Cold water may be used.Wash clothing before reuse. Thoroughly clean shoes before reuse. Get medical attention immediately.

Serious Skin Contact:
Wash with a disinfectant soap and cover the contaminated skin with an anti-bacterial cream. Seek immediate medical attention.

Inhalation:
If inhaled, remove to fresh air. If not breathing, give artificial respiration. If breathing is difficult, give oxygen. Get medical attention immediately.

Serious Inhalation:
Evacuate the victim to a safe area as soon as possible. Loosen tight clothing such as a collar, tie, belt or waistband. If breathing is difficult, administer oxygen. If the victim is not breathing, perform mouth-to-mouth resuscitation. WARNING: It may be hazardous to the person providing aid to give mouth-to-mouth resuscitation when the inhaled material is toxic, infectious or corrosive. Seek immediate medical attention.

Ingestion:
Do NOT induce vomiting unless directed to do so by medical personnel. Never give anything by mouth to an unconscious person. Loosen tight clothing such as a collar, tie, belt or waistband. Get medical attention if symptoms appear.

Serious Ingestion: Not available.

Section 5: Fire and Explosion Data

Flammability of the Product: Flammable.

Auto-Ignition Temperature: 438°C (820.4°F) **Flash**

Points: CLOSED CUP: 50°C (122°F). **Flammable**

Limits: Not available.

Products of Combustion: These products are carbon oxides (CO, CO2).

Fire Hazards in Presence of Various Substances:
Extremely flammable in presence of open flames and sparks. Highly flammable in presence of heat.

Explosion Hazards in Presence of Various Substances:
Risks of explosion of the product in presence of mechanical impact: Not available. Risks of explosion of the product in presence of static discharge: Not available.

Fire Fighting Media and Instructions:
Flammable liquid, soluble or dispersed in water. SMALL FIRE: Use DRY chemical powder. LARGE FIRE: Use alcohol foam, water spray or fog. Cool containing vessels with water jet in order to prevent pressure build-up, autoignition or explosion.

Special Remarks on Fire Hazards: Not available.

Special Remarks on Explosion Hazards: Not available.

Section 6: Accidental Release Measures

Small Spill:
Dilute with water and mop up, or absorb with an inert dry material and place in an appropriate waste disposal container.

Large Spill:
Flammable liquid. Corrosive liquid. Poisonous liquid. Keep away from heat. Keep away from sources of ignition. Stop leak if without risk. Absorb with DRY earth, sand or other non-combustible material. Do not get water inside container. Do not touch spilled material. Use water spray curtain to divert vapor drift. Use water spray to reduce vapors. Prevent entry into sewers, basements or confined areas; dike if needed. Call for assistance on disposal. Be careful that the product is not present at a concentration level above TLV. Check TLV on the MSDS and with local authorities.

Section 7: Handling and Storage

Precautions:
Keep locked up.. Keep container dry. Keep away from heat. Keep away from sources of ignition. Ground all equipment containing material. Do not ingest. Do not breathe gas/fumes/ vapor/spray. Never add water to this product. If ingested, seek medical advice immediately and show the container or the label. Avoid contact with skin and eyes. Keep away from incompatibles such as oxidizing agents, acids, alkalis, moisture.

Storage:
Store in a segregated and approved area. Keep container in a cool, well-ventilated area. Keep container tightly closed and sealed until ready for use. Avoid all possible sources of ignition (spark or flame).

Section 8: Exposure Controls/Personal Protection

Engineering Controls:
Provide exhaust ventilation or other engineering controls to keep the airborne concentrations of vapors below their respective threshold limit value. Ensure that eyewash stations and safety showers are proximal to the work-station location.

Personal Protection:
Face shield. Full suit. Vapor respirator. Be sure to use an approved/certified respirator or equivalent. Gloves. Boots.

Personal Protection in Case of a Large Spill:
Splash goggles. Full suit. Vapor respirator. Boots. Gloves. A self contained breathing apparatus should be used to avoid inhalation of the product. Suggested protective clothing might not be sufficient; consult a specialist BEFORE handling this product.

Exposure Limits:
TWA: 2 (ppm) from ACGIH (TLV) [United States] [1997] TWA: 2 [Australia] STEL: 20 (ppm) [United Kingdom (UK)] TWA: 10 (ppm) [United Kingdom (UK)] Consult local authorities for acceptable exposure limits.

Section 9: Physical and Chemical Properties

Physical state and appearance: Liquid.

Odor: Acrid (Strong.) **Taste:** Not

available.

Molecular Weight: 72.06 g/mole **Color:**

Colorless.

pH (1% soln/water): Not available.

Boiling Point: 141°C (285.8°F)

Melting Point: 14°C (57.2°F)

Critical Temperature: 342°C (647.6°F)

Specific Gravity: 1.05 (Water = 1) **Vapor**

Pressure: 0.5 kPa (@ 20°C)

Vapor Density: 2.5 (Air = 1) **Volatility:**

Not available.

Odor Threshold: 0.092 ppm

Water/Oil Dist. Coeff.: The product is more soluble in oil; log(oil/water) = 0.4

Ionicity (in Water): Not available.

Dispersion Properties:
Partially dispersed in methanol, diethyl ether. See solubility in water.

Solubility:
Soluble in cold water. Very slightly soluble in acetone. Insoluble in diethyl ether.

Section 10: Stability and Reactivity Data

Stability: The product is stable.

Instability Temperature: Not available.

Conditions of Instability: Not available.

Incompatibility with various substances:
Extremely reactive or incompatible with oxidizing agents, acids, alkalis. Reactive with moisture.

Corrosivity:
Slightly corrosive in presence of steel, of aluminum, of zinc, of copper. Non-corrosive in presence of glass.

Special Remarks on Reactivity: Not available.

Special Remarks on Corrosivity: Not available.

Polymerization: Yes.

Section 11: Toxicological Information

Routes of Entry: Absorbed through skin. Dermal contact. Eye contact. Inhalation.

Toxicity to Animals:
WARNING: THE LC50 VALUES HEREUNDER ARE ESTIMATED ON THE BASIS OF A 4-HOUR EXPOSURE. Acute oral toxicity (LD50): 2400 mg/kg [Mouse]. Acute dermal toxicity (LD50): 294 mg/kg [Rabbit]. Acute toxicity of the vapor (LC50): 75 6 hours [Monkey].

Chronic Effects on Humans:
CARCINOGENIC EFFECTS: A4 (Not classifiable for human or animal.) by ACGIH, 3 (Not classifiable for human.) by IARC. MUTAGENIC EFFECTS: Classified POSSIBLE for human. Mutagenic for mammalian germ and somatic cells. TERATOGENIC EFFECTS: Classified SUSPECTED for human. DEVELOPMENTAL TOXICITY: Classified Reproductive system/toxin/male [POSSIBLE]. Classified Development toxin [SUSPECTED]. Causes damage to the following organs: bladder, brain, upper respiratory tract, eyes, central nervous system (CNS).

Other Toxic Effects on Humans:
Very hazardous in case of skin contact (permeator), of eye contact (corrosive). Hazardous in case of skin contact (corrosive), of inhalation (lung corrosive).

Special Remarks on Toxicity to Animals: Not available.

Special Remarks on Chronic Effects on Humans: Not available.

Special Remarks on other Toxic Effects on Humans: Not available.

Section 12: Ecological Information

Ecotoxicity:
Ecotoxicity in water (LC50): 130 mg/l 24 hours [Trout]. 460 mg/l 96 hours [Trout]. 270 mg/l 24 hours [Water flea].

BOD5 and COD: Not available.

Products of Biodegradation:
Possibly hazardous short term degradation products are not likely. However, long term degradation products may arise.

Toxicity of the Products of Biodegradation: The products of degradation are less toxic than the product itself.

Special Remarks on the Products of Biodegradation: Not available.

Section 13: Disposal Considerations

Waste Disposal:

Section 14: Transport Information

DOT Classification: Class 8: Corrosive material

Identification: : Acrylic Acid, Inhibited UNNA: UN2218 PG: II

Special Provisions for Transport: Not available.

Section 15: Other Regulatory Information

Federal and State Regulations:
Rhode Island RTK hazardous substances: Acrylic Acid Pennsylvania RTK: Acrylic Acid Florida: Acrylic Acid Minnesota: Acrylic Acid Massachusetts RTK: Acrylic Acid New Jersey: Acrylic Acid TSCA 8(b) inventory: Acrylic Acid TSCA 5(e) substance consent order: Acrylic Acid TSCA 8(a) IUR: Acrylic Acid TSCA 12(b) annual export notification: Acrylic Acid SARA 313 toxic chemical notification and release reporting: Acrylic Acid CERCLA: Hazardous substances.: Acrylic Acid: 1 lbs. (0.4536 kg)

Other Regulations: OSHA: Hazardous by definition of Hazard Communication Standard (29 CFR 1910.1200).

Other Classifications:

WHMIS (Canada):
CLASS B-3: Combustible liquid with a flash point between 37.8°C (100°F) and 93.3°C (200°F). CLASS E: Corrosive liquid.

DSCL (EEC):

HMIS (U.S.A.):

- **Health Hazard:** 3
- **Fire Hazard:** 2
- **Reactivity:** 2
- **Personal Protection:**

National Fire Protection Association (U.S.A.):

- **Health:** 3
- **Flammability:** 2

Reactivity: 2

Specific hazard:

Protective Equipment:
Gloves. Full suit. Vapor respirator. Be sure to use an approved/certified respirator or equivalent. Wear appropriate respirator when ventilation is inadequate. Face shield.

Section 16: Other Information

References: Not available.

Other Special Considerations: Not available.

Created: 10/09/2005 03:37 PM

Last Updated: 11/01/2010 12:00 PM

Material Safety Data Sheet

Carbon Dioxide

Airgas

Section 1. Chemical product and company identification

Product Name	: Carbon Dioxide
Supplier	: AIRGAS INC., on behalf of its subsidiaries 259 North Radnor-Chester Road Suite 100 Radnor, PA 19087-5283 1-610-687-5253
Product use	: Synthetic/Analytical chemistry.
MSDS#	: 001013
Date of Preparation/Revision	: **4/11/2005.**
In case of emergency	: 1-800-949-7937

Section 2. Composition, Information on Ingredients

Name	CAS number	% Volume	Exposure limits
Carbon Dioxide	124-38-9	100	**ACGIH TLV (United States, 9/2004).** STEL: 54000 mg/m³ 15 minute(s). Form: All forms STEL: 30000 ppm 15 minute(s). Form: All forms TWA: 9000 mg/m³ 8 hour(s). Form: All forms TWA: 5000 ppm 8 hour(s). Form: All forms **NIOSH REL (United States, 6/2001).** STEL: 54000 mg/m³ 15 minute(s). Form: All forms STEL: 30000 ppm 15 minute(s). Form: All forms TWA: 9000 mg/m³ 10 hour(s). Form: All forms TWA: 5000 ppm 10 hour(s). Form: All forms **OSHA PEL (United States, 6/1993).** TWA: 9000 mg/m³ 8 hour(s). Form: All forms TWA: 5000 ppm 8 hour(s). Form: All forms

Section 3. Hazards identification

Physical state : Gas.

Emergency overview : Warning!

CONTENTS UNDER PRESSURE.

CAUSES DAMAGE TO THE FOLLOWING ORGANS: LUNGS, CARDIOVASCULAR SYSTEM, SKIN, EYES, CENTRAL NERVOUS SYSTEM, EYE, LENS OR CORNEA. MAY CAUSE RESPIRATORY TRACT, EYE AND SKIN IRRITATION.

Avoid contact with skin and clothing. Avoid breathing gas. Do not puncture or incinerate container. Keep container closed. Use only with adequate ventilation. Wash thoroughly after handling.

Contact with rapidly expanding gas, liquid, or solid can cause frostbite.

Routes of entry : Inhalation,Dermal,Eyes

Potential acute health effects

- **Eyes** : Moderately irritating to the eyes.
- **Skin** : Moderately irritating to the skin.
- **Inhalation** : Moderately irritating to the respiratory system.
- **Ingestion** : Ingestion is not a normal route of exposure for gases

Carbon Dioxide

Potential chronic health effects : **CARCINOGENIC EFFECTS**Not available. :
MUTAGENIC EFFECTS Not available. :
TERATOGENIC EFFECTS Not available. :

Medical conditions aggravated by overexposure : Acute or chronic respiratory conditions may be aggravated by overexposure to this gas.

See toxicological Information (section 11)

Section 4. First aid measures

No action shall be taken involving any personal risk or without suitable training.If fumes are still suspected to be present, the rescuer should wear an appropriate mask or a self-contained breathing apparatus.It may be dangerous to the person providing aid to give mouth-to-mouth resuscitation.

Eye contact : In case of contact, immediately flush eyes with plenty of water for at least 15 minutes. Get medical attention immediately.

Skin contact : In case of contact, immediately flush skin with plenty of water. Remove contaminated clothing and shoes. Wash clothing before reuse. Thoroughly clean shoes before reuse. Get medical attention.

Frostbite : Try to warm up the frozen tissues and seek medical attention.

Inhalation : If inhaled, remove to fresh air. If not breathing, give artificial respiration. If breathing is difficult, give oxygen. Get medical attention.

Ingestion : Do NOT induce vomiting unless directed to do so by medical personnel. Never give anything by mouth to an unconscious person. Get medical attention if symptoms appear.

Section 5. Fire fighting measures

Flammability of the product : Non-flammable.

Fire fighting media and instructions : Use an extinguishing agent suitable for surrounding fires.

If involved in fire, shut off flow immediately if it can be done without risk. Apply water from a safe distance to cool container and protect surrounding area.

No specific hazard.

Special protective equipment for fire-fighters : Fire fighters should wear appropriate protective equipment and self-contained breathing apparatus (SCBA) with a full facepiece operated in positive pressure mode.

Section 6. Accidental release measures

Personal precautions : Immediately contact emergency personnel. Keep unnecessary personnel away. Use suitable protective equipment (Section 8). Shut off gas supply if this can be done safely. Isolate area until gas has dispersed.

Environmental precautions : Avoid dispersal of spilled material and runoff and contact with soil, waterways, drains and sewers.

Section 7. Handling and storage

Handling : Avoid contact with eyes, skin and clothing. Keep container closed. Use only with adequate ventilation. Do not puncture or incinerate container. Wash thoroughly after handling. High pressure gas. Use equipment rated for cylinder pressure. Close valve after each use and when empty. Protect cylinders from physical damage; do not drag, roll, slide, or drop. Use a suitable hand truck for cylinder movement.
Never allow any unprotected part of the body to touch uninsulated pipes or vessels that contain cryogenic liquids. Prevent entrapment of liquid in closed systems or piping without pressure relief devices. Some materials may become brittle at low temperatures and will easily fracture.

Storage : Keep container tightly closed. Keep container in a cool, well-ventilated area. Cylinders should be stored upright, with valve protection cap in place, and firmly secured to prevent falling or being knocked over. Cylinder temperatures should not exceed 52 °C (125 °F).

Carbon Dioxide

Section 8. Exposure Controls, Personal Protection

Engineering controls : Use only with adequate ventilation. Use process enclosures, local exhaust ventilation, or other engineering controls to keep airborne levels below recommended exposure limits.

Personal protection

Eyes : Safety eyewear complying with an approved standard should be used when a risk assessment indicates this is necessary to avoid exposure to liquid splashes, mists or dusts.

When working with cryogenic liquids, wear a full face shield.

Skin : Personal protective equipment for the body should be selected based on the task being performed and the risks involved and should be approved by a specialist before handling this product.

Respiratory : Use a properly fitted, air-purifying or air-fed respirator complying with an approved standard if a risk assessment indicates this is necessary.Respirator selection must be based on known or anticipated exposure levels, the hazards of the product and the safe working limits of the selected respirator.

The applicable standards are (US) 29 CFR 1910.134 and (Canada) Z94.4-93

Hands : Chemical-resistant, impervious gloves or gauntlets complying with an approved standard should be worn at all times when handling chemical products if a risk assessment indicates this is necessary.

Insulated gloves suitable for low temperatures

Personal protection in case of a large spill : A self-contained breathing apparatus should be used to avoid inhalation of the product.

Consult local authorities for acceptable exposure limits.

Section 9. Physical and chemical properties

Molecular weight	: 44.01 g/mole
Molecular formula	: CO2
Boiling/condensation point	: -78.55°C (-109.4°F)
Melting/freezing point	: Sublimation temperature: -78.5°C (-109.3°F)
Critical temperature	: 30.9°C (87.6°F)
Vapor pressure	: 830 psig **Vapor**
density	: 1.53 (Air = 1)
Specific Volume (ft³/lb)	: 8.77193
Gas Density (lb/ft³)	: 0.114
Physical chemical comments	: Not available.

Section 10. Stability and reactivity

Stability and reactivity : The product is stable.

Section 11. Toxicological information

Toxicity data

IDLH : 40000 ppm

Chronic effects on humans : Causes damage to the following organs: lungs, cardiovascular system, skin, eyes, central nervous system (CNS), eye, lens or cornea.

Other toxic effects on humans

Specific effects

Carcinogenic effects

Mutagenic effects

Reproduction toxicity

Build 1.1

Carbon Dioxide

Section 12. Ecological information

Products of degradation	**:** These products are carbon oxides (CO, CO_2).
Toxicity of the products of biodegradation	**:** The product itself and its products of degradation are not toxic.
Environmental fate	**:** Not available.
Environmental hazards	**:** No known significant effects or critical hazards. **:** Not
Toxicity to the environment	available.

Section 13. Disposal considerations

Product removed from the cylinder must be disposed of in accordance with appropriate Federal, State, local regulation.Return cylinders with residual product to Airgas, Inc.Do not dispose of locally.

Section 14. Transport information

Regulatory information	UN number	Proper shipping name	Class	Packing group	Label	Additional information
DOT Classification	UN1013 UN2187	CARBON DIOXIDE Carbon dioxide, refrigerated liquid	2.2	Not applicable (gas).		**Limited quantity** Yes. **Packaging instruction** **Passenger Aircraft** Quantity limitation: 75 kg **Cargo Aircraft** Quantity limitation: 150 kg
TDG Classification	UN1013 UN2187	CARBON DIOXIDE Carbon dioxide, refrigerated liquid	2.2	Not applicable (gas).		**Explosive Limit and Limited Quantity Index** 0.125 **Passenger Carrying Road or Rail Index** 75
Mexico Classification	UN1013 UN2187	CARBON DIOXIDE Carbon dioxide, refrigerated liquid	2.2	Not applicable (gas).		-

Carbon Dioxide

Section 15. Regulatory information

United States

U.S. Federal regulations : TSCA 8(b) inventory: Carbon Dioxide

SARA 302/304/311/312 extremely hazardous substances: No products were found.
SARA 302/304 emergency planning and notification: No products were found.
SARA 302/304/311/312 hazardous chemicals: Carbon Dioxide
SARA 311/312 MSDS distribution - chemical inventory - hazard identification: Carbon Dioxide: Sudden Release of Pressure, Immediate (Acute) Health Hazard, Delayed (Chronic) Health Hazard

Clean Water Act (CWA) 307: No products were found. Clean

Water Act (CWA) 311: No products were found.

Clean air act (CAA) 112 accidental release prevention: No products were found.

Clean air act (CAA) 112 regulated flammable substances: No products were found.

Clean air act (CAA) 112 regulated toxic substances: No products were found.

State regulations : Pennsylvania RTK: Carbon Dioxide: (generic environmental hazard)
Massachusetts RTK: Carbon Dioxide
New Jersey: Carbon Dioxide

Canada

WHMIS (Canada) : Class A: Compressed gas.

CEPA DSL: Carbon Dioxide

Section 16. Other information

United States

Label Requirements : CONTENTS UNDER PRESSURE.
CAUSES DAMAGE TO THE FOLLOWING ORGANS: LUNGS, CARDIOVASCULAR SYSTEM, SKIN, EYES, CENTRAL NERVOUS SYSTEM, EYE, LENS OR CORNEA. MAY CAUSE RESPIRATORY TRACT, EYE AND SKIN IRRITATION.

Canada

Label Requirements : Class A: Compressed gas.

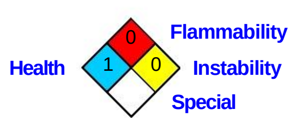
Hazardous Material Information System (U.S.A.) :

Health	*	1
Fire hazard		0
Reactivity		0
Personal protection		C

liquid:

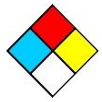
Health		3
Fire hazard		0
Reactivity		0
Personal protection		

National Fire Protection Association (U.S.A.) :



liquid:

Build 1.1



Carbon Dioxide

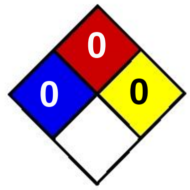
0 **Flammability**

Health 3 0 **Instability**

Special

Notice to reader

To the best of our knowledge, the information contained herein is accurate. However, neither the above named supplier nor any of its subsidiaries assumes any liability whatsoever for the accuracy or completeness of the information contained herein.
Final determination of suitability of any material is the sole responsibility of the user. All materials may present unknown hazards and should be used with caution. Although certain hazards are described herein, we cannot guarantee that these are the only hazards that exist.



Health	0
Fire	0
Reactivity	0
Personal Protection	A

Material Safety Data Sheet
Water MSDS

Section 1: Chemical Product and Company Identification

Product Name: Water

Catalog Codes: SLW1063

CAS#: 7732-18-5

RTECS: ZC0110000

TSCA: TSCA 8(b) inventory: Water

CI#: Not available.

Synonym: Dihydrogen oxide

Chemical Name: Water

Chemical Formula: H2O

Contact Information:

Sciencelab.com, Inc.
14025 Smith Rd.
Houston, Texas 77396

US Sales: **1-800-901-7247**
International Sales: **1-281-441-4400**

Order Online: ScienceLab.com

CHEMTREC (24HR Emergency Telephone), call:
1-800-424-9300

International CHEMTREC, call: 1-703-527-3887

For non-emergency assistance, call: 1-281-441-4400

Section 2: Composition and Information on Ingredients

Composition:

Name	CAS #	% by Weight
Water	7732-18-5	100

Toxicological Data on Ingredients: Not applicable.

Section 3: Hazards Identification

Potential Acute Health Effects:
Non-corrosive for skin. Non-irritant for skin. Non-sensitizer for skin. Non-permeator by skin. Non-irritating to the eyes. Non-hazardous in case of ingestion. Non-hazardous in case of inhalation. Non-irritant for lungs. Non-sensitizer for lungs. Non-corrosive to the eyes. Non-corrosive for lungs.

Potential Chronic Health Effects:
Non-corrosive for skin. Non-irritant for skin. Non-sensitizer for skin. Non-permeator by skin. Non-irritating to the eyes. Non-hazardous in case of ingestion. Non-hazardous in case of inhalation. Non-irritant for lungs. Non-sensitizer for lungs. CARCINOGENIC EFFECTS: Not available. MUTAGENIC EFFECTS: Not available. TERATOGENIC EFFECTS: Not available. DEVELOPMENTAL TOXICITY: Not available.

Section 4: First Aid Measures

Eye Contact: Not applicable.

Skin Contact: Not applicable.

Serious Skin Contact: Not available.

Inhalation: Not applicable.

Serious Inhalation: Not available.

Ingestion: Not Applicable

Serious Ingestion: Not available.

Section 5: Fire and Explosion Data

Flammability of the Product: Non-flammable.

Auto-Ignition Temperature: Not applicable. **Flash**

Points: Not applicable.

Flammable Limits: Not applicable.

Products of Combustion: Not available.

Fire Hazards in Presence of Various Substances: Not applicable.

Explosion Hazards in Presence of Various Substances: Not Applicable **Fire**

Fighting Media and Instructions: Not applicable. **Special Remarks on Fire**

Hazards: Not available.

Special Remarks on Explosion Hazards: Not available.

Section 6: Accidental Release Measures

Small Spill: Mop up, or absorb with an inert dry material and place in an appropriate waste disposal container.

Large Spill: Absorb with an inert material and put the spilled material in an appropriate waste disposal.

Section 7: Handling and Storage

Precautions: No specific safety phrase has been found applicable for this product.

Storage: Not applicable.

Section 8: Exposure Controls/Personal Protection

Engineering Controls: Not Applicable

Personal Protection: Safety glasses. Lab coat.

Personal Protection in Case of a Large Spill: Not Applicable

Exposure Limits: Not available.

Section 9: Physical and Chemical Properties

Physical state and appearance: Liquid.

Odor: Odorless.

Taste: Not available.

Molecular Weight: 18.02 g/mole **Color:**

Colorless.

pH (1% soln/water): 7 [Neutral.]

Boiling Point: 100°C (212°F) **Melting**

Point: Not available.

Critical Temperature: Not available.

Specific Gravity: 1 (Water = 1)

Vapor Pressure: 2.3 kPa (@ 20°C)

Vapor Density: 0.62 (Air = 1) **Volatility:**

Not available.

Odor Threshold: Not available.

Water/Oil Dist. Coeff.: Not available. **Ionicity**

(in Water): Not available.

Dispersion Properties: Not applicable

Solubility: Not Applicable

Section 10: Stability and Reactivity Data

Stability: The product is stable.

Instability Temperature: Not available.

Conditions of Instability: Not available.

Incompatibility with various substances: Not available.

Corrosivity: Not available.

Special Remarks on Reactivity: Not available.

Special Remarks on Corrosivity: Not available.

Polymerization: Will not occur.

Section 11: Toxicological Information

Routes of Entry: Absorbed through skin. Eye contact.

Toxicity to Animals:
LD50: [Rat] - Route: oral; Dose: > 90 ml/kg LC50: Not available.

Chronic Effects on Humans: Not available.

Other Toxic Effects on Humans:
Non-corrosive for skin. Non-irritant for skin. Non-sensitizer for skin. Non-permeator by skin. Non-hazardous in case of ingestion. Non-hazardous in case of inhalation. Non-irritant for lungs. Non-sensitizer for lungs. Non-corrosive to the eyes. Non-corrosive for lungs.

Special Remarks on Toxicity to Animals: Not available.

Special Remarks on Chronic Effects on Humans: Not available.

Special Remarks on other Toxic Effects on Humans: Not available.

Section 12: Ecological Information

Ecotoxicity: Not available.

BOD5 and COD: Not available.

Products of Biodegradation:
Possibly hazardous short term degradation products are not likely. However, long term degradation products may arise.

Toxicity of the Products of Biodegradation: The product itself and its products of degradation are not toxic.

Special Remarks on the Products of Biodegradation: Not available.

Section 13: Disposal Considerations

Waste Disposal:
Waste must be disposed of in accordance with federal, state and local environmental control regulations.

Section 14: Transport Information

DOT Classification: Not a DOT controlled material (United States).

Identification: Not applicable.

Special Provisions for Transport: Not applicable.

Section 15: Other Regulatory Information

Federal and State Regulations: TSCA 8(b) inventory: Water

Other Regulations: EINECS: This product is on the European Inventory of Existing Commercial Chemical Substances.

Other Classifications:

WHMIS (Canada): Not controlled under WHMIS (Canada).

DSCL (EEC):
This product is not classified according to the EU regulations. Not applicable.

HMIS (U.S.A.):

- **Health Hazard:** 0
- **Fire Hazard:** 0
- **Reactivity:** 0
- **Personal Protection:** a

National Fire Protection Association (U.S.A.):

- **Health:** 0
- **Flammability:** 0
- **Reactivity:** 0
- **Specific hazard:**

Protective Equipment:
Not applicable. Lab coat. Not applicable. Safety glasses.

Section 16: Other Information

References: Not available.

Other Special Considerations: Not available.

Created: 10/10/2005 08:33 PM

Last Updated: 11/01/2010 12:00 PM

Material Safety Data Sheet
J. R. Simplot Company
AgriBusiness

M12000

Trade Name: Phosphoric Acid
Registration No: None

SECTION 1 — CHEMICAL PRODUCT AND COMPANY INFORMATION

Manufacturer or Formulator: J.R. Simplot Company
P.O. Box 70013
Boise, ID 83707
Emergency Phone - Chemtrec: 1-800-424-9300

Product Name: Phosphoric Acid
Common Name: Phosphoric Acid
Chemical Type: Phosphoric Acid

SECTION 2 — COMPOSITION/INFORMATION ON INGREDIENTS

Chemical Name and Synonyms	C.A.S. No.	Chemical Formula	WT%	TLV	PEL
			Hazardous		
Phosphoric Acid AS	7664-38-2	H_3PO_4	34-70	1 mg/M^3 3 mg/M^3 STEL	1 mg/m3
			Non-Hazardous		
None listed			Balance		

SECTION 3 — HAZARDS IDENTIFICATION

Ingestion: Ingestion may result in irritation and burning of mucous membranes and/or gastrointestinal tract.
Inhalation: Inhalation of acid mist may produce mild to severe irritation of respiratory tract. Some rail cars of Phosphoric acid may have an off gas of chlorine. Follow proper unloading procedures on this sheet under section 7 to eliminate possible exposure. Will produce severe irritation.
Eye Contact: Prolonged contact may result in burn to eye causing permanent damage. May produce mild to severe irritations. Prolonged contact may
Skin Absorption: result in chemical burns. May produce mild to severe irritations. Prolonged contact may result in chemical burns.
Skin Contact: Severe conjunctivitis which may result in permanent damage. Can result in nausea and vomiting with severe abdominal pain.
Effects of Overdose: Prolonged contact with acid mist can result in severe respiratory irritation.

SECTION 4 — FIRST AID MEASURES

Dilute with 2-3 glasses of milk or water. Do not induce vomiting. Consult a physician immediately.
Ingestion: Remove person to fresh air. If person is not breathing, perform artificial respiration if properly trained. Seek medical attention
Inhalation: immediately.
Promptly flush eyes with clean, cool water for at least 15 minutes. Contact a physician immediately. Promptly
Eyes: remove contaminated clothing and rinse area with clear water for 15 minutes.
Skin:

SECTION 5 — FIRE FIGHTING MEASURES

Non-flammable. Use media suitable to extinguish source of fire.
Extinguishing Media:
Special Fire Fighting Procedures: When phosphoric acid mists from hot fires may be encountered, self-contained breathing apparatus (SCBA) should be worn.
Unusual Fire and Explosion Hazards: Not listed

SECTION 6 — ACCIDENTAL RELEASE MEASURES

Environmental Precautions: Low toxicity to aquatic life. Do not contaminate any watercourse or other body of water by direct application, disposal, or cleaning of equipment.
Steps to be taken in case material is released or spilled:
Dike around spill for containment and recover for re-processing. Small spills can be safely neutralized with limestone or soda ash. Caustic soda should be avoided because of excessive reactivity.

SECTION 7 — HANDLING AND STORAGE

Precautions to be taken in handling and storing:
When unloading a rail car always open vent valve on top of rail car before opening dome and let sit an adequate amount of time to mitigate possible exposure to any off gas of chlorine. Always wear proper protective equipment. Avoid storage and/or transfer in tanks, lines and other equipment constructed or materials not specifically designed and approved for phosphoric acid service. Avoid freezing weather below 1ºF. Have adequate first aid water available.

SECTION 8 — EXPOSURE CONTROLS/PERSONAL PROTECTION

Ventilation Protection: General area ventilation.
Respiratory Protection: Approved respirators suitable for protection against acid mists and vapors. Not required for normal work procedures, but if misting occurs and always during unloading, use a high efficiency particulate respirator or self-contained breathing apparatus, with a full face shield when exposed above the TLV. Check with respirator manufacturer to determine the appropriate type of equipment for a given application.
Protective Clothing: Rubber clothing, chemical gloves, footwear and chemical hat or hood suitable for protection against acids. Tight
Eye Protection: sealing splash proof goggles.
Other: Eyewash and safety shower in work areas.

Trade Name: Phosphoric Acid **M12000**
Registration No: None

SECTION 9 PHYSICAL AND CHEMICAL PROPERTIES

Boiling Point:	Approx. 270ºF @ 1 atmosphere	**Solubility in Water:**	Complete
Density:	1.39 - 2.00 Sp. Gr.	**% Volatiles (by volume):**	<1.0
Flashpoint:	Not applicable	**Vapor Pressure, mm Hg:**	5.0 @ 78ºF
pH:	Strongly acidic; <1.0	**Reaction with Water:**	Exothermal, produces heat.
Appearance:	Green, viscous liquid. Odorless when cold; pungent when hot.		
Extinguishing Media:	Non-flammable. Use media suitable to extinguish source of fire.		

SECTION 10 STABILITY AND REACTIVITY

Stability (Normal Conditions): Stable
Conditions to Avoid: Avoid contact with strong alkalies or metals other than certain stainless steels.
Incompatibility (Material to Avoid): Reacts violently with strong alkalies producing heat. Contact with many metals may result in severe corrosion attack of the metal and liberation of hydrogen gas. High temperatures will liberate phosphorus oxides. Will not occur.

Hazardous Decomposition Products:
Hazardous Polymerization:

TOXICOLOGY INFORMATION

SECTION 11

Acute Oral Toxicity: LD_{50} (rat) is greater than 1,530 mg/kg; not acutely toxic by oral exposure. (TFI Product Testing Results, OECD Guideline 425)
Acute Dermal Toxicity: LD_{50} (rat) is greater than 3,160 mg/kg (ppm); not acutely toxic by dermal exposure. (TFI Product Testing Results, OECD Guideline 402).
Acute Inhalation Toxicity: LC_{50} (guinea pig, mouse, rat, rabbit) is 61-1,689 mg/m³; highly toxic by inhalation. (TFI Product Testing Results)
Acute Fish Toxicity: 96-hour LC_{50} is 3.0-3.5 mg/L (ppm); moderate toxicity to aquatic organisms. (TFI Product Testing Results, OECD Guideline 203)

SECTION 12 ECOLOGICAL INFORMATION

None listed.

SECTION 13 DISPOSAL CONSIDERATIONS

Waste disposal Procedures: Collect and reprocess where possible. Following neutralization with limestone or soda ash, consult local, state and federal regulations before final disposal.

SECTION 14 TRANSPORT INFORMATION

Shipping name: RQ Phosphoric Acid, 8, UN1805, P.G. III

Hazard Class:	8	**C.A.S. Number:**	7664-38-2
Reportable Quantity (RQ):	5000 lbs.	**D.O.T. Number:**	UN1805
Labels Required:	Corrosive	**Haz Waste No:**	D002
Placard:	Corrosive	**EPA Regist No:**	None
Packaging Group:	III		

Refer to 49 CFR 172.101 Hazardous Material Table for further provisions, packaging authorizations and quantity limitations.

SECTION 15 REGULATORY INFORMATION

Carcinogenicity: by IARC?: Yes ( ) No (X) by NTP?: Yes ( ) No (X)

This product contains phosphoric acid, CAS No. 7664-38-2, which is subject to the reporting requirements of section 313 of Title III of the Superfund Amendments Act of 1986 and 40 CFR Part 372.

SECTION 16 OTHER INFORMATION

Flash Point (Test Method):	Non-flammable	**Flammable Limits**	**LOWER**	**UPPER**
Autoignition Temperature:	Not applicable	(% BY VOLUME)	N/A	N/A

Hazard Rating (N.F.P.A.): **Health:** 2 **Fire:** 0 **Reactivity:** 0 **Specific:** Not applicable
This N.F.P.A. rating is a recommendation by the manufacturer using the guidelines or published evaluations prepared by the National Fire Protection Association (N.F.P.A.).

MSDS Version Number: 6 (revisions to Section 11)

Reviewed by: The Department of Regulatory Affairs
June 2001 (208) 672-2700

Material Safety Data Sheet

Dextrose, Anhydrous

Revised: 10/13/2011 **Replaces:** 09/27/2011
Printed: 10/13/2011

Carolina Biological Supply Company
2700 York Rd | Burlington, NC 27215 • to order: 800.334.5551 • for support: 800.227.1150
CAROLINA www.carolina.com

Section 1 - Product Description

Product Name: Dextrose, Anhydrous
Product Code(s): 17-1025, 20-2200, 20-2500, 20-2051, 85-7430, 85-7442, 85-7450, 85-7451, 85-7452, 84-0550, 84-0996, 84-0491, 10-1026, 25-1012, PD1031, C61411, C71928, C70137, C19346, C70510
Size: Various
Chemical Name: Dextrose
CAS Number: 50-99-7
Formula: $C_6H_{12}O_6$
Synonyms: D-Glucose, Grape Sugar, Corn Sugar
Distributor: Carolina Biological Supply Company, 2700 York Road, Burlington, NC 27215
Chemical Information: 800-227-1150 (8am-5pm (ET) M-F) **Chemtrec** 800-424-9300 (Transportation Spill Response 24 hours)

Section 2 - Hazard Identification

Emergency Overview: Non-Hazardous under normal use.
Potential Health Effects:
Eyes: May cause irritation.
Ingestion: May cause gastrointestinal discomfort.
Skin: May cause irritation to skin.
Inhalation: May cause irritation to respiratory tract.

Section 3 - Composition / Information on Ingredients

Principal Hazardous Components: Dextrose, Anhydrous
TLV units: N/A **PEL units:** N/A

Section 4 - First Aid Measures

Emergency and First Aid Procedures:
Eyes - In case of contact with eyes, rinse immediately with plenty of water and seek medical advice.
Skin - After contact with skin, take off immediately all contaminated clothing, and wash immediately with plenty of water.
Ingestion - If swallowed, do not induce vomiting: seek medical advice immediately and show this container or label. If swallowed, rinse mouth with water (only if the person is conscious).
Inhalation - In case of accident by inhalation: remove casualty to fresh air and keep at rest.

Section 5 - Firefighting Procedures

Flash Point (Method Used): N/A
NFPA Rating:
Health: 0
Fire: 1
Reactivity: 0
Extinguisher Media: Use media suitable to extinguish surrounding fire.
Flammable Limits in Air % by Volume: N/A
Autoignition Temperature: N/A
Special Firefighting Procedures: Firefighters should wear full protective equipment and NIOSH approved self-contained breathing apparatus.
Unusual Fire and Explosion Hazards: None

Section 6 - Spill or Leak Procedures

Steps to Take in Case Material Is Released or Spilled: Ventilate area of spill. Clean-up personnel should wear proper protective equipment. Avoid creating dust. Sweep or scoop up and containerize for disposal.

Section 7 - Special Precautions

Precautions to Take in Handling or Storing: Do not breathe dust. Keep container dry.
After contact with skin, wash immediately with plenty of water.
Harmful if swallowed. Keep container tightly closed in a cool, well-ventilated place.

Section 8 - Protection Information

Respiratory Protection (Specify Type): None needed under normal conditions of use with adequate ventilation. A NIOSH/MSHA chemical cartridge respirator should be worn if PEL or TLV is exceeded.
Ventilation:
Local Exhaust: Preferred
Mechanical(General): Acceptable
Special: No **Other:** No
Protective Gloves: Natural rubber, Neoprene, PVC or equivalent.
Eye Protection: Splash proof chemical safety goggles should be worn.
Other Protective Clothing or Equipment: Lab coat, apron, eye wash, safety shower.

Section 9 - Physical Data

Molecular Weight: 198.17 g/mol
Boiling Point: Decomposes
Vapor Density(Air=1): 6.3
Percent Volatile by Volume: 0%
Solubility in Water: Slightly Soluble
Melting Point: 146 °C
Vapor Pressure: N/A
Specific Gravity (H2O=1): 1.544
Evaporation Rate (BuAc=1): N/A
Appearance and Odor: White, odorless crystals.

Section 10 - Reactivity Data

Stability: Stable
Conditions to Avoid: Explosive when mixed with oxidising substances.
Incompatibility (Materials to Avoid): Oxidizers,
Hazardous Decomposition Products: COx,
Hazardous Polymerization: Will not occur

Section 11 - Toxicity Data

Toxicity Data: orl-rt LD50: 25,800 mg/kg
Effects of Overexposure:

Acute: See Section 2
Chronic: Not listed as a carcinogen by IARC, NTP or OSHA. Mutation data cited. Reproductive data cited.
Conditions Aggravated by Overexposure: None Known
Target Organs: No information available **Primary**
Route(s) of Entry: Inhalation.

Section 12 - Ecological Data

EPA Waste Numbers: N/A

Section 13 - Disposal Information

Waste Disposal Methods: Dispose in accordance with all applicable Federal, State and Local regulations. Always contact a permitted waste disposer (TSD) to assure compliance.

Section 14 - Transport Information

DOT Proper Shipping Name: N/A

Section 15 - Regulatory Information

EPA TSCA Status: On TSCA Inventory
Hazard Category for SARA Section 311/312 Reporting: Acute

Name List:	**Chemical Category:**
No	No

CERCLA Section 103 RQ(lb.): No
RCRA Section 261.33: No

Section 16 - Additional Information

The information provided in this Material Safety Data Sheet represents a compilation of data drawn directly from various sources available to us. Carolina Biological Supply makes no representation or guarantee as to the suitability of this information to a particular application of the substance covered in the Material Safety Data Sheet. Any employer must carefully assess the applicability of any information contained herein in regards to the particular use to which the employer puts the material.

Glossary

ACGIH	American Conference of Governmental Industrial Hygienists
CAS Number	Chemical Services Abstract Number
CERCLA	Comprehensive Environmental Response, Compensation, and Liability Act
DOT	U.S. Department of Transportation
IARC	International Agency of Research on Cancer
N/A	Not Available
NTP	National Toxicology Program
OSHA	Occupational Safety and Health Administration
PEL	Permissible Exposure Limit
ppm	Parts per million
RCRA	Resource Conservation and Recovery Act
SARA	Superfund Amendments and Reauthorization Act
TLV	Threshold Limit Value
TSCA	Toxic Substances Control Act